UNIVERSIDADE DA CORUÑA

Facultad de Ciencias
Departamento de Biología Celular y Molecular

ASSESSMENT OF PASSIVE OPTICAL REMOTE SENSING FOR MAPPING MACROALGAE COMMUNITIES ON THE GALICIAN COAST

Tesis doctoral

Gema Casal Pascual

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Assessment of passive optical remote sensing for mapping macroalgae communities on the Galician coast

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Esta tesis está dedicada a todos los que me habéis apoyado durante todo este proceso, tanto en el terreno profesional como en el personal, y que de alguna u otra manera me habéis "obligado" a continuar hasta al final.

This thesis is dedicated to all who have supported me, both professionally and personally, throughout this process. Somehow or another, you have made me continue until the end.

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RESUMO

As zonas costeiras representan a transición entre o ambiente acuático e o terrestre sendo un dos ecosistemas máis dinámicos e productivos da Terra. As comunidades de algas bentónicas xogan un papel fundamental neste tipo de ecosistemas. Dada a súa importancia ecolóxia e económica fanse necesarios métodos que permitan unha recolección de información tanto cuantitativa como cualitativa para a súa eficiente valoración, monitorización e xestión. Os Sistemas de Información Xeográfica (SIX) e a teledetección teñen un uso potencial na xeración de información xeográfica. Sen embargo, durante o planteamento desta tese, en Galicia encontrábase dispoñible escasa información para os usuarios e na maioría dos casos era de pouco detalle ou o proceso administrativo para a súa adquisición demasiado arduo. Por esta razón, esta tese foi orixinalmente deseñada como unha contribución á xeración de datos xeográficos dixitales da zona litoral, donde a escaseza é máis significante. Neste sentido, dixitalizouse unha liña de costa de Galicia e valoráronse varios sensores remotos para o cartografiado de comunidades de algas. Estes sensores permitiron a diferenciación de grupos algais ata unha profundidade determinada dependendo da súa resolución espectral e espacial.

RESUMEN

Las zonas costeras representan la transición entre el ambiente acuático y el terrestre siendo una de los ecosistemas más dinámicos y productivos de la Tierra. Las comunidades de algas bentónicas juegan un papel fundamental en este tipo de ecosistemas. Dada su importancia ecológica y económica se hacen necesarios métodos que permitan una recolección de información tanto cuantitativa como cualitativa para su eficiente valoración, monitorización y gestión. Los Sistemas de Información Geográfica (SIG) y la teledetección tienen un uso potencial en la generación de información geográfica. Sin embargo, durante el planteamiento de esta tesis, en Galicia se encontraba escasa información disponible para los usuarios y en la mayoría de los casos, esta información era de muy poco detalle o el proceso administrativo para su adquisición demasiado arduo. Por esta razón, esta tesis fue originalmente diseñada como una contribución a la generación de datos geográficos digitales de la zona litoral, donde la escasez es más significante. En este sentido se digitalizó una línea de costa de Galicia y se valoraron varios sensores remotos para el cartografiado de comunidades de algas. Estos sensores permitieron la diferenciación de grupos algales hasta una profundidad determinada dependiendo de su resolución espectral y espacial.

ABSTRACT

Coastal zones represent the transition between terrestrial and aquatic environment being one of the most dynamic and productive ecosystems on the Earth. Benthic algal communities play an important role in coastal ecosystems. Due to their ecological and economic importance there is a strong need for methods that allow collecting quantitative and qualitative information about macroalgal benthic communities, in order to allow their efficient assessment, monitoring and management. Geographical Information Systems (GIS) and remote sensing (RS) have a potential use in the generation of digital geographic information. However, at the beginning of this thesis the lack of information in Galicia related to this field was remarkable. Only little information was available for users and in most of the cases it was

too coarse or the administrative process for data acquisition too arduous. For this reason, this thesis was originally designed as a contribution for the generation of digital geographic data for the littoral zone, where this scarcity was more significant. In this sense a shoreline of Galicia was digitized and several kind of remote sensors were assessed to map macroalgal communities. These sensors allowed the differentiation of different macroalgal groups until an specific depth depending on their spectral and spatial resolution.

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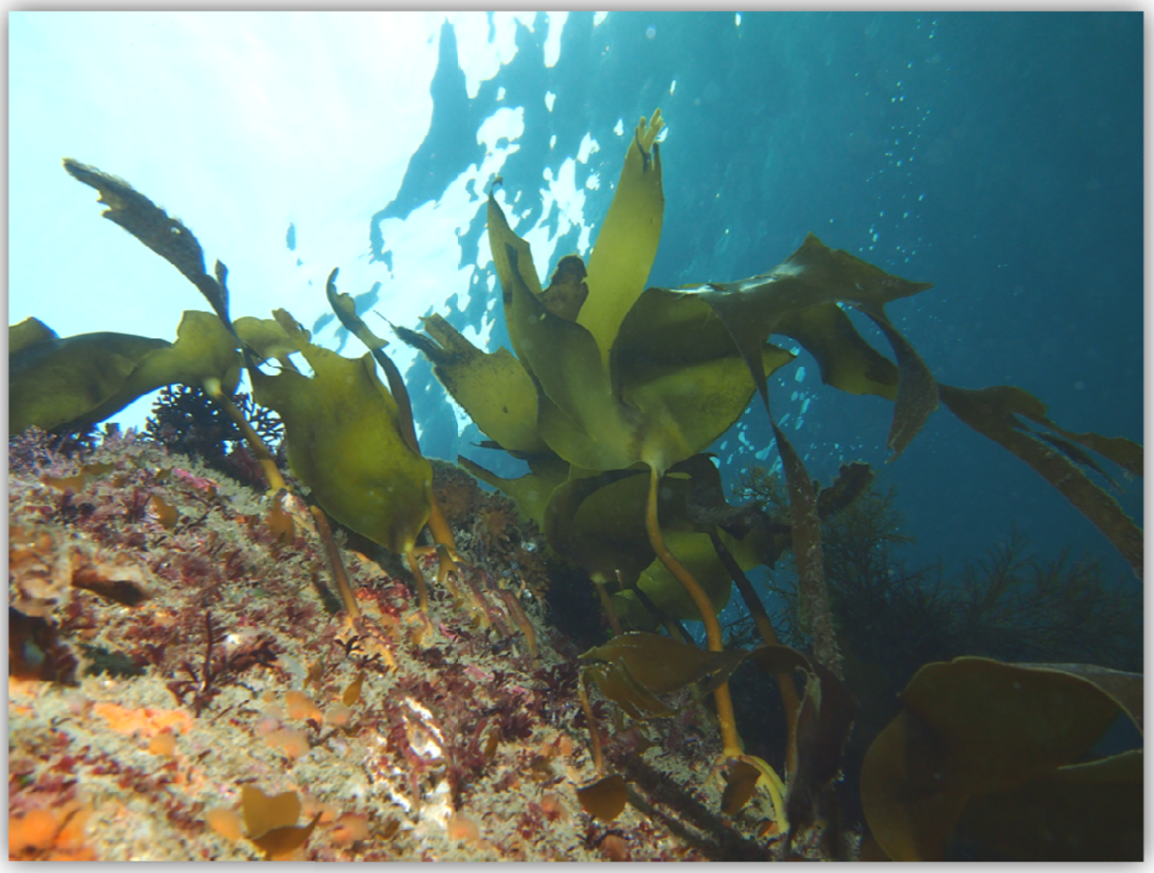

GENERAL INTRODUCTION

GENERAL INTRODUCTION

Coastal zones represent the transition between terrestrial and aquatic environment being one of the most dynamic and productive ecosystems on the Earth (Cicin-Sain, 2006; Yang, 2009). Benthic algal communities play an important role in coastal ecosystems due to their ecological functions. These communities are essential habitat for many organisms (Birkett et al. 1998; Cacabelos et al. 2010), mating and nursery grounds even for commercial species like cod (*Gadus morhua*) or pollock (*Pollachius pollachius*) (Sjøtun et al., 1993; Borg *et al*. 1997; Shaffer 2003), feeding areas (Velando and Freire, 1999; Lorentsen *et al*. 2004) and refuge (Bushmann 1990; Gotceitas *et al*. 1997). Another relevant aspect is their important contribution to primary production, for example some research on kelp forests, as those present on the Galician coast, show productions higher than 4000 gC/m^2·year (Mohammed and Fredriksen 2004). These communities also contribute to the sediment stabilization and coastline protection (Madsen *et al*. 2001), besides being a suitable indicator on the ecological status of coastal communities (Juanes *et al*. 2008). On the other hand, the interest for the commercial use of some algal species has increased in the last years in many parts of the world (Vasquez 2008; Vea and Ask 2011). This situation is also found on the Galician coast (Cremades *et al*. 2004) where specific exploitation plans were established.

Macroalgal communities can be altered or damaged by the introduction of invasive species, climate change or by anthropogenic actions such as fishing, aquaculture farms or contamination. In certain places, the cause of these alterations has not established as occur in the variation of kelp forests on the Galician coast. Due to their ecological and economic importance, there is a strong need for methods that allow collecting quantitative and qualitative information about macroalgal benthic communities, in order to allow their efficient assessment, monitoring and management. The use of remote sensing is well established to study this kind of vegetation due to its advantages with regard to traditional field methods. Among these advantages, it can be mentioned that these techniques are non-invasive, allow to study large areas, mapping inaccessible zones as well as provide a repetitive cover of a target area. Its repetitive coverage offers archive data for detection of changes over time, and these digital data can be easily integrated into Geographic Information Systems (GIS) for further analyses (Green and King, 2005; Cassata and Collins, 2008). While remote sensing constitutes an information source that can describe and monitor a variety of systems at different scales, from local to global, GIS can be used as a spatial analysis tool providing a platform for data integration, synthesis and modelling to support decision making, essential in many coastal applications.

Despite of the potential utility of remote sensing to map benthic habitats, this technique presents some limitations that should be taken into account before its application. The potential of marine remote sensing can be sometimes overpraised, which result in the disappointment of the users who not consider these limitations. Thus, to avoid disappointing results it is necessary to understand the fundamental limitations, such as wavelength-specific penetration of light trough the water, spectral mixing within a pixel and atmospheric attenuation (Holden and LeDrew, 1998). The importance of each source of error or limitation will depend on the aim of the remote sensing application and will vary from sensor to sensor. Other factors that should be taken into account are the meteorological conditions of the study zone. The presence of clouds can result in useless images or, in the case of temporal monitoring, in an important reduction of suitable images.

1. General historical review

The term "remote sensing" could be defined as the science and art of obtaining information about an object, area or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area o phenomenon under investigation[1]. It was first time used by Ms. Evelyn Pruitt of the U.S. Office of Naval Research in 1950 (Walker, 2006). In spite of the modern environmental remote sensing (as it is used nowadays) is a relatively young discipline, remote sensing has been practiced for long time. For this reason, to understand the fast development as well as the importance and influence that this technique has nowadays, in many and different fields, it is necessary to look back at its past.

It is difficult to establish an only and fixed event where remote sensing started to be used. Perhaps one of the oldest references were the astronomic observations of Galileo Galilei at the beginning of 17th century (~1600)[2]. Galileo with a home-made telescope carried out important studies and discoveries. In those days he studied, among others, the moon's phases and its surface. He also observed some stars and planets such as the moons of Jupiter, known nowadays as Galilean satellites in his honour, the Rings of Saturn or the phases of Venus and published some data about his observations.

A century later, the first graphic reference of a man observing the ground from above was registered. This fact occurred in 1794 during the Battle of Fleurus (present-day Belgium)[3]. In this battle a balloon built by the Montgolfier brothers was used for the observation of the enemy movements. From this moment on, advances in remote sensing were related to military purposes until relatively recent years where civil sensors were launched. Since the man could be elevated from the ground to make observations, it had to wait nearby another century in order to the first known aerial photography could be taken. It was around 1858 when Gaspard-Félix Tournachon tried to perform land surveys using aerial photography from tethered balloons (Schott, 1989). Some years later, in the 1880s, Arthur Batut affixed cameras to kites publishing a book on kite aerial photography in 1890 (Gernsheim and Gernsheim, 1969) (Fig.1).

[1] http://earthobservatory.nasa.gov/Features/RemoteSensing/ last accessed 10 May 2012

[2] http://www.gis.usu.edu/~doug/RS5750/lectures/L2_Sensors.pdf last accessed 10 May 2012

[3] National Air and Space Museum, Smithsonian Institution, Washington No.76-1196

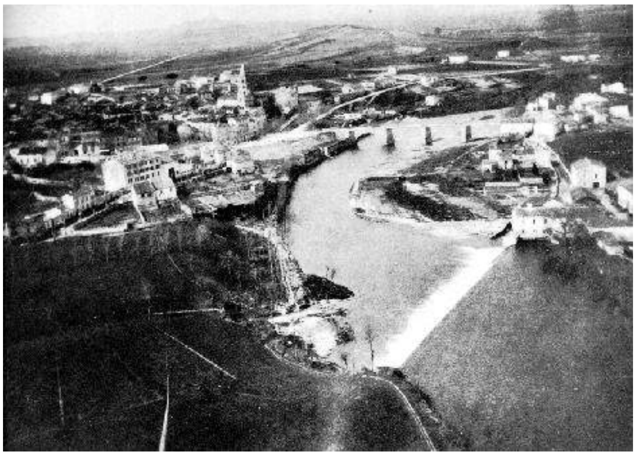

Fig. 1. Labruguiere from the air in 1889, an image by Arthur Batut[4].

The use of cameras on balloons and kites did not contribute in an efficient way, being quite instable and the obtained results needed to be improved. Around 1900 appeared, with military purposes, the Bavarian Pigeon Corps. At that time little cameras were fixed to pigeons' bodies taking photographs every 30 seconds[5] (Fig.2). On the other hand, during these years, new advances were being done in the aeronautic science. Thus, on 17th December 1903 the first piloted flight took place (Wegener, 1986). In 1908 the first photograh from an aircraft was taken. The photographer was L.P. Bonvillain a passenger of Wright brothers' flight (Jessen et al., 2006).

Fig. 2. Example of cameras fixed to pigeons' bodies[6].

It was necessary to wait until 1915 for the apparition of the first aerial camera. This aerial camera was developed by J.T.C. Moore-Brabazon during the World War I (WWI) (1914-1918)[7]. Due to the importance of this new perspective of acquiring information, in the last months of the war a big amount of photographs were taken by both sides of the conflict. After this big step, the second boost in remote sensing techniques was linked to the World War II (WWII). During WWII aerial photography techniques and information interpretation were highly

[4] http://arch.ced.berkeley.edu/kap/background/history1.html last accessed 10 May 2012

[5] http://northstargallery.com/aerialphotography/history%20aerial%20photography/history.htm last accessed 10 May 2012

[6] http://www.oldaerialphotos.com/History_of_Aerial_Photography.cfm last accessed 10 May 2012

[7] http://userpages.umbc.edu/~tbenja1/umbc7/santabar/vol1/lec1/1-2.html last accessed 10 May 2012

developed. The development of remote sensing continued during the Cold War where the first artificial satellite, Sputnik 1, was launched into the space by the Soviet Union (1957). After the Sputnik, many civil and military missions appeared. Among them, it could be remarked the first Earth Observation satellite launched in 1960. It was the TIROS-1 satellite launched by NASA and destined for meteorological studies. During those years the crewed missions such as Mercury (1961), Gemini-Titán (1965) and Apollo (since 1968), all of them belonging to NASA, allowed to obtain the first space photographs for civil use.

Regarding environmental purposes, it was in 1972 when NASA launched the first Earth Resources Technology Satellite (ERTS-1), subsequently renamed Landsat. This was the point of departure for many other sensors destined to Earth observation and their data have been used in countless applications. After this moment, satellites devoted to meteorological (e.g. METEOSAT, MetOp), terrestrial (e.g Landsat, SPOT) and oceanic processes (e.g. SeaWifs, AVHRR) and many other applications has been launched. The different temporal, spatial, spectral and radiometric resolutions from airborne and spaceborne platforms offer a large amount of combinations that can be useful in different applications. Most part of these applications appeared in a relatively short period and continue being developed very fast as they will be in the future.

2. Brief historical review and current situation of remote sensing in Spain (1889- 2012)

Few references exist regarding the historical context of remote sensing in Spain. These scarce references can be found in some texts related to cartography or geography and on the websites of different organisations. In the last years, information related to this field can be also found in some blogs, not always specifically related with remote sensing. Moreover, we have not found any text that provides an overview of the Spanish historical context. For this reason, it would be useful to include some references here to set the background of the present thesis. It is necessary to mention that this historical review does not intend to be comprehensive only to reflect the evolution of remote sensing from its beginning until nowadays.

1889

The first remote sensing applications in Spain appeared in the 19th century and were related to military purposes. In 1884 the Military Aerostation was created. However, the scarcity of material and budget problems involved that the real birth of the aerostation was delayed until 1889 (Quirós-Linares and Fernández-García, 1996). During this year, photography attempts from balloons flights were carried out (La ilustración española americana, 1889). An important figure during those years was D. Rafael Peralta who obtained photographs from balloons and designed important equipments for the application of aerophotogrametric methods (Quirós-Linares and Fernández-García, 1996).

1909

In that year an Aerostatic Unit was sent to Morocco. Among its functions was the recognition of the enemy territory using photographs and draws (Quirós-Linares and Fernández-García, 1996) (Fig.3).

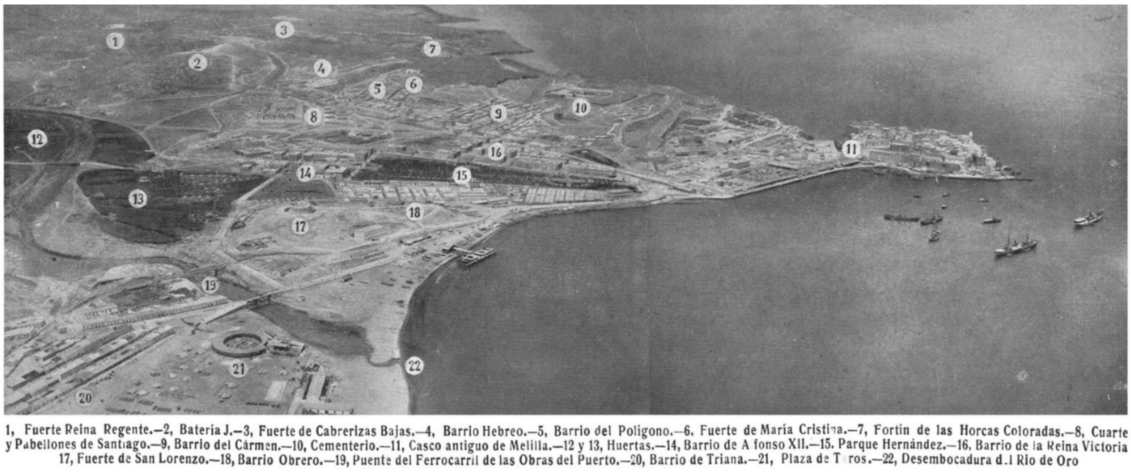

Fig. 3. Photograph taken over Melilla City from the military balloon "Jupiter" (1910). The numbers correspond with the different districts and important locations[8].

1920

In the 20th century (26th January 1920), the *Servicio Geográfico y Laboratorio Meteorológico* (Geographic Service and Meteorological Laboratory) of the air forces was established in Cuatro Vientos (Madrid). This event is considered as the official origin of aero-photocartografic activities in Spain[9]. Thus, during the Morocco War an important number of photographic flights were carried out. These flights were destined to generate a topographic map of the Protectorate[10] with a scale of 1:50000 (Nadal et al., 2000).

1927

Some years later, in 1927 and with civil purposes, a photogrametric flight was performed. It covered a vast zone of the Ebro Basin at a scale of 1:10000 (Galván-Plaza, 2007; Montaner et al., 2010). These aerial photographs are probably the oldest ones over the Spanish territory that are conserved nowadays. They can be downloaded from the *Confenderación Hidrográfica del Ebro*, CHE (Ebro Hidrographic Confederation) website[11] (Fig.4.).

Due to the importance that remote sensing was acquiring at that moment new institutions which were dedicated to its promotion and development appeared. Thus, in 1927 the *Junta*

[8] http://patrimonioculturalmelillense.blogspot.com.es/2009_04_01_archive.html last accessed 10 May 2012
[9] http://www.ejercitodelaire.mde.es last accessed 10 May 2012
[10] Territory in the North of Morocco where Spain exerted its Protectorate during the period 1913–1956.
[11] http://oph.chebro.es/fotoplanos.htm last accessed 10 May 2012

Constituyente de la Sociedad Española de Fotogrametría (Incorporating Board for the Spanish Society of Photogrammetry) was created. This organisation developed its activity until 1936[12].

Fig. 4. Aerial photography over Zaragoza city (1927). Source: CHE

1936-1939

During the Spanish Civil War the use of aerial photographic cameras was an efficient way of obtaining useful territorial information for both sides of the conflict. During this period a high number of aerial mosaics and panoramic views were taken. The photographs were devoted to military purposes such as covering conflict fronts, cities as well as military objectives to prepare bombings and assess their results (Fernández-García, 2004). During the Civil War only the US Air Forces took more than 171 million of photographs for cartographic purposes covering around 40 million of square kilometres (Servicio Geográfico del Ejército, 1970).

1940

Some years later, between 1940 and 1944 the German army carried out a new cartographic flight over Andalusia[13]. At the same time, the *Real Sociedad Geográfica* (Geographic Royal Society), founded in 1876, represented Spain in the International Society for Photogrammetry and Remote Sensing (ISPRS) from 1940 to 1977[14].

1942

In 1942 an organisation that would be key in Spanish remote sensing was founded. This organisation is the Instituto *Nacional de Técnica Aeroespacial*, INTA (National Institute for

[12] http://www.secft.org/secft,1,1,quienes-somos.html last accessed 10 May 2012
[13]http://www.diariodesevilla.es/article/ocio/387080/alemanes/y/aliados/cartografiaron/andalucia/durante/la/ii/guerra/mundial.html last accessed 10 May 2012
[14] http://www.secft.org/secft,1,1,quienes-somos.html last accessed 10 May 2012

Aerospace Technology)[15]. The INTA would develop an intense activity, first in the aeronautical and subsequently in the space field. Currently, INTA is expanded in several centres across the Spanish territory. These centres constitute fundamental nodes in the space programmes of ESA and NASA and are[16]:

- Villafranca del Castillo (Madrid) space station, which is one of the ESA stations for communications with space vehicles.
- Robledo de Chavela (Madrid) space communications complex, that forms part of the NASA Deep Space stations network.
- Canary Islands (Maspalomas) space centre, specialised in the operation of Earth observation and geo-stationary satellites.
- El Arenosillo Experimentation Centre (Huelva), devoted to atmospheric research and space rockets.
- Granada Test Centre that performs flight tests to certificate aircrafts.

1945-1946

Between 1945 and 1946 a photographic flight with cartographic purposes was carried out over the peninsular territory and Balearic Islands by US Air Forces. No reference exists that the flight was carried out over Canary archipelago (Urteaga et al., 2000). This flight is technically known as “Serie A”. The height of the flight varied from 5700 m to 8800 m involving a scale range from 1:34700 to 1:50500 (Quirós-Linares and Fernández-García, 1997). The flight was carried out according to the National Topographic Map. For this reason the film rolls have equivalence with this map grid (Urteaga et al., 2000). The material of this flight is formed by 435 film rolls. However, the material characteristics and the storage conditions during 50 years caused damage to some of the film rolls (Quirós-Linares and Fernández-García, 1997). The material of this flight is nowadays conserved in the *Centro Fotográfico y Cartográfico del Ejército del Aire*, CECAF (Photographic and Cartographic Centre of Air Forces).

1956-1957

Between 1956 and 1957 a second flight that covered the whole Spanish territory took place. This work was cooperation between Spanish and US Air Forces and was carried out for a cartographic purpose. This flight is colloquially known as “American flight”. The photographs were taken at 5000 m height with a scale of 1:33000 (Urteaga et al., 2000). This information belongs to *Ministerio de Defensa* (Ministry of Defense) and some Autonomic Communities such as Andalusia, Madrid, Catalonia or Navarra have published on the Internet the photograhs that cover their territory. Recently, in September 2011, the Ministry of Defense delivered a digital copy of this flight (Serie B) to the *Instituto Geográfico Nacional*, IGN (National Geographic Institute). However, in April 2012, this information was not yet available for users.

[15] http://www.inta.es/NuestraHistoria.aspx last accessed 10 May 2012
[16] http://www.inta.es/DondeEstamos.aspx last accessed 10 May 2012

1974

The first Spanish satellite, named INTASAT, was launched on 15th November 1974 with a lifespan of two years[17]. This small satellite was developed by INTA in collaboration with Construcciones Aeronaúticas (CASA), Standard Eléctrica (nowadays Alcatel), the British company Hawker Siddeley Dynamics (HSD) and NASA. The aim of this satellite was to carry out two experiments: a scientific experiment to study the ionosphere and a technological experiment designed to measure the effect of space radiation on some new CMOS components (Jiménez- Dolera, 1974).

1975

In 1975 the European Space Agency (ESA) was created by merging two organizations ELDO (the European Launcher Development Organization) with ESRO (the European Space Research Organization)[18]. Spain was one of its founder members along with Belgium, Germany, Denmark, France, United Kingdom, Italy, the Netherlands, Sweden and Switzerland. Ireland joined later in the same year.

Since then, more countries such as Austria, Finland, Norway and Portugal, and most recently Greece, Luxembourg and the Czech Republic have joined them. Romania signed its Accession Agreement with ESA on 20th January, 2011 and on 23th December became the 19th State Member. Hungary, Poland, Estonia and Slovenia are 'European Cooperating States' and other countries have signed cooperation agreements with ESA like Canada.

ESA's programmes are designed to find out more about Earth, its space environment, the Solar System and the Universe, as well as to develop satellite-based technologies and services, and to promote European industries. ESA also works closely with space organisations outside Europe[19]. Besides its variety of programs it is necessary to mention the Third Party Missions Program (TPM) Category-1. This program has been worked for more than 30 years, providing EO (Earth Observation) data.

The Third Party Missions scheme currently includes over 50 instruments on more than 30 missions. Data of Category 1 are directly provided by ESA to the scientific community at cost of reproduction. ESA provides an Earth Observation Principal Investigator Portal at: http://eopi.esa.int. This website contains information about all Earth observation data that is accessible through ESA, including the TPM data. Users can apply for data access; find publications on science results and news; and access an online searchable database of all science projects.

[17] http://www.inta.es/noticias/documentos/INTASAT.pdf last accessed 10 May 2012
[18] http://www.esa.int/SPECIALS/Space_Year_2007/SEM7VFEVL2F_0.html last accessed 10 May 2012
[19] http://www.esa.int/SPECIALS/About_ESA/SEMW16ARR1F_0.html last accessed 10 May 2012

1977

In 1977 the *Sociedad Española de Cartografía, Fotogrametría y Teledetección*, SECFYT (Spanish Society of Cartography, Photogrammetry and Remote Sensing) was created[20]. This organisation had the purpose of integrating the activities that were being carried out by the *Real Sociedad Geográfica* (Geographic Society Royal) and the *Seminario Español de Estudios Cartográficos de la Asociación Española para el progreso de las Ciencias* (Spanish Seminar of Cartographic Studies of the Spanish Association to the Science Progress).

In this year, the *Centro para el Desarrollo Tecnológico Industrial*, CDTI (Centre for Industrial Technological Development) was also created. The CDTI is a Business Public Entity, dependent on the current *Ministerio de Economía y Competitividad* (Ministry of Economy and Competitiveness), which fosters the technological development and innovation of Spanish companies. The CDTI manages and helps Spanish companies to obtain high-technology industrial contracts generated by different national and European organisations, such as the European Space Agency (ESA), the European Laboratory for Particle Physics (CERN), the European Synchrotron (ESRF), Hispasat and Eumetsat[21].

1986

Years later, in March 1986, the *Grupo de Trabajo en Teledetección*, GTT (Working Group on Remote Sensing) was founded. In September 1988 this group constituted the *Asociación Española de Teledetección*, AET (Spanish Association of Remote Sensing)[22]. This association has organized up to now 14 scientific congresses as well as numerous scientific meetings. Moreover, it has published every semester since 1993 the *Revista Española de Teledetección* (Spanish Journal of Remote Sensing)[23].

1995

In 1995 the first astronaut born in Spain travelled to the outer space in the Mission Specialist (MS)-2, STS-73 Columbia. Miguel E. López Alegría was born in Madrid in 1958 but grew up in California. However, he declined the Spanish nationality to join NASA[24]. He took part in three Space Shuttle missions and one International Space Station (ISS) mission. Until this moment he carried out ten EVAs (work done outside of spacecraft) and currently he holds the American EVA record in duration and number. In March, 2012 he abandoned NASA[25].

1998

In 1998, the first Spanish astronaut travelled to space. Pedro Duque (Madrid, 1963)[26], flew as Mission Specialist on the Space Shuttle Discovery, STS-95. The nine-day mission was dedicated

[20] http://www.secft.org/einzelartikel.php?kat=1&subkat=11&subid=11 last accessed 10 May 2012
[21] http://www.cdti.es/index.asp?MP=6&MS=5&MN=1 last accessed 10 May 2012
[22] http://www.aet.org.es/?q=presentacion last accessed 10 May 2012
[23] http://www.aet.org.es/?q=revista last accessed 10 May 2012
[24] http://www.jsc.nasa.gov/Bios/htmlbios/lopez-al.html last accessed 10 May 2012
[25] http://www.nasa.gov/home/hqnews/2012/mar/HQ_12-077_Lopez_Alegria_Departs.html last accessed 10 May 2012
[26] http://www.esa.int/esaCP/ESASZCZ84UC_Spain_0.html last accessed 10 May 2012

to research in weightlessness and to the study of the Sun. Duque was responsible, among others, for the five ESA scientific facilities on board and for the extensive computer system and configurations used on the Shuttle. He was the Executive President of Deimos Imaging S.L. during five years, the company responsible for the first Spanish private satellite launched in 2009.

2000

The European Facility for Airborne Research (EUFAR) was born in 2000 and is an integrating activity of the European infrastructures in aerial research. It was funded by the European Commission under FP5/FP6/FP7. The main objectives of EUFAR Program could be summarized in the following ones: to develop trans-national access to national infrastructures, to reduce redundancy and fill the gaps, to improve the service by strengthening expertise through exchange of knowledge, development of standards and protocols, constitution of data bases and promote the use of airborne research infrastructures, especially for young scientists from countries where such facilities are lacking[27].

The National Institute for Aerospace Science (INTA) takes actively in the EUFAR subprogram Transnational Access (TA) with its aerial platforms and atmospheric research (Díaz de Aguilar et al., 2005). The purpose of TA consists of facilitating access to the most significant platforms in Europe funded in its entirety for researchers. The INTA makes available two aircrafts CASA 212 and 200. The atmospheric research platform has the necessary equipment to measure, not only the flight parameters but also the basic atmospheric parameters, clouds and aerosol microphysics and atmospheric chemistry. Moreover, INTA contributes with the following sensors: Airborne Hyperspectral Scanner (AHS), Airborne Thematic Mapper (ATM) and Airborne Multiespectral Digital Camera.

2003

In 2003 the Cervantes Mission[28], dependent on ESA, took place. The aim of this spatial mission was the development of European scientific experiments, most of them Spanish and that were carried out by the Spanish astronaut, Pedro Duque. The experiments were related to life and physical science, Earth observation, education and new technologies, including experiments in the Microgravity Science Glovebox, a research facility developed in Europe.

2004

In 2004 the *Plan Nacional de Teledetección* (PNT)[29] (National Plan of Remote Sensing) was created inside the *Plan Nacional de Observación del Territorio* (PNOT) (National Plan for Territory Observation). It is coordinated by the *Instituto Geográfico Nacional* (National Geographic Institute) and the *Centro Nacional de Información Geográfica* (National Centre of Geographic Information). Both organisations belong to the *Ministerio de Fomento* (Ministry of Building). Its main aim is to coordinate the satellite images acquisition over the Spanish

[27] http://www.eufar.net/ last accessed 10 May 2012
[28] http://www.esa.int/esaMI/Cervantes_mission_Spanish/index.html last accessed 10 May 2012
[29] http://www.ign.es/PNT/ last accessed 10 May 2012

territory between Ministries and Autonomic Governments. The PNT is in charge of carrying out a basic pre-processing (geometric and radiometric correction) of the images as well as their free distribution to the whole Public Administration such as universities and public research institutes. Periodic acquisitions of PNT include high, medium and low space resolution images.

High spatial resolution category includes images from 0.5 m of pixel size to 10 m in panchromatic and from 5 m to 30 m in multispectral mode. These images have the purpose of environmental information and geographical data bases with medium and high scales (1:200000 to 1:1000000). In this category SPOT-5 satellite images are included. Some examples of these applications are the SIOSE I and II project (*Sistema de Información sobre Ocupación del Suelo en España*, Information System about Soil Occupation in Spain) related to land cover and land used in Spain, the CORINE that corresponds with the Land Cover Project from European Union, the MCA (*Mapa de Cultivos y Aprovechamientos*, Crop and Land Use Map) or the MFE (*Mapa Forestal de España*, Forest Map of Spain)[30].

In the medium spatial resolution category, images with a spatial resolution between 10 and 15 m in panchromatic mode and from 20 to 50 m in multispectral mode are included. The applications of these images are related to temporal monitoring of environmental issues such as soil cover, crops identification, forest information or areas recovered from natural and anthropologic hazards (e.g. burnt areas) and their derivative effects. These images are also useful in the environmental management where remote sensing is combined with Geographical Information Systems[31]. At this moment images from Landsat-5TM and from the new satellite Deimos-1 have been taken. In a short period of time available images from Sentinel-2 are also expected (GMES program).

Finally, the low resolution images category corresponds with multispectral images from 50 to 5000 m of spatial resolution. The data and derivate products are mainly applied to the analysis of processes that change over time. Their daily availability allows monitoring in almost real time the Earth surface. This characteristic is especially favourable in the analysis of environmental variables such as the vegetative state of crops, humidity degree on the land surface … Thus, the main uses of these low resolution images are the calculation of biophysical and environmental parameters such as Vegetation Index, Leaf Area Index (LAI), fire hazard, etc. [32]The sensors used here are MERIS, MODIS, AQUA/TERRA and in the future Sentinel-3.

Regarding water environment the data that PNT offers can be considered scarce. It seems that there is a lack of applications and derivate products in this sense. PNT only offers inland water parameters from MERIS that are used in the *Directiva Marco del Agua* (Water Framework Directive) or the *Directiva de Aguas de Baño* (Bathing Water Directive). However, no references have been found about products for the coastal zone.

The images and derivate products of PNT are stored in a server and can be downloaded through FTP service for public administrations and scientists without charging. However, a

[30] http://www.ign.es/PNT/alta_resolucion.html last accessed 10 May 2012
[31] http://www.ign.es/PNT/media_resolucion.html last accessed 10 May 2012
[32] http://www.ign.es/PNT/baja_resolucion.html last accessed 10 May 2012

publishing campaign would be recommended because the existence of these products is unknown for many potential users.

2007

Spanish government started the *Plan Estratégico para el Sector Espacial 2007-2011* (Strategic Plan for the Spatial Sector 2007-2011). This plan was managed by the *Ministerio de Industria* (Ministry of Industry) through Centre for Industrial Technological Development (CDTI) and it contributed with a big economic investment in the development and promotion of remote sensing.

2008

ESA's European Space Astronomy Centre (ESAC), located in Villanueva de la Cañada (Madrid), was inaugurated on 7th February 2008 and has an increasingly central role in ESA's astronomy and planetary missions. The European Space Astronomy Centre (ESAC) receives data from deep-space ground stations worldwide. The huge volume of data that comes back to Earth from space has to be calibrated and translated into a format that can be exploited by scientists. ESAC has been chosen as the site for the Science Operations Centres (SOCs) of ESA Science missions for both astronomy and the Solar System. This means ESAC is rapidly evolving into a scientific hot-spot, a meeting point for top-level international space scientists working on different, but closely-related areas[33].

2009

In 2009, Deimos-1[34], the first Spanish private satellite for Earth Observation was launched. Experts who belong to Remote Sensing Laboratory (University of Valladolid) associated to Deimos Imaging [35]are in charge of processing the data obtained with this satellite all over the planet. The satellite applications are related to all type of information over the Earth such as agriculture, fires control and monitoring, spills, etc.

2012

As this thesis is located in Galicia, it should be mentioned here the launch of Xatcobeo satellite on 13th February, 2012. Xatcobeo project[36] is a joint project between INTA and the University of Vigo. This picosatellite (10 x 10 x 10 cm and 1 kg) has a spanlife of several months and transport a software defined reconfigurable radio (SRAD), a system for measuring the amount of ionizing radiation (RDS) and an experimental solar panel deployment system (PDM).

Towards the future

The Ministry of Defense and Ministry of Industry have carried out a high investment in the building of two new satellites: Ingenio previously named SEOSAT and Paz previously named

[33] http://www.esa.int/esaMI/ESAC/ last accessed 10 May 2012
[34] http://www.deimos-imaging.com/tecnologia/satelite-deimos-1 last accessed 10 May 2012
[35] http://www.deimos-imaging.com/ last accessed 10 May 2012
[36] http://www.xatcobeo.com/cms/index.php last accessed 10 May 2012

SEOSAR that will belong to Spanish Earth Observation Satellite System. Both satellites will be built in Spain and could be operating in 2012. Ingenio will be devoted to take optical images while Paz will be equipped with a radar sensor. The constellation will have civil and military uses such as the study of natural disasters, watch borders or providing information to the Spanish army. While, Ingenio will be controlled by CDTI, the Ministry of Defense will control Paz and both will be operated by Hisdesat Company. Besides Ingenio and Paz, the Spanish leadership is confirmed in future initiatives such as SmallGEO (2012), Sentinel-3 (2013) or Proba-3 (2016) among others.

Remote sensing data allow obtaining geographic and environmental information of the Earth surface in a periodic way and in many different spectral, radiometric and spatial resolutions. For these reasons, more and more companies and public organisations such as the General State Administration and Autonomic Governments are integrating this kind of data in their projects. Universities have also played a key role in remote sensing development and spreading. In the last years new specialized courses have appeared and this discipline is also included as a subject during degree, Master or doctorate studies. However, there are issues that should be improved in the future to make easier the use of remote sensing and to increase its derivative products. Among these issues are a large economic effort, the bureaucratic management and the license or copyright restrictions that sometimes make difficult the use of the data.

As mentioned before, it could be said that Spain has strongly bet on remote sensing and in the last years new organisations and projects have arisen related to this field. Spanish Government has carried out a big economic investment making possible that Spain takes part actively in important projects such as the building of new satellites, research, data reception or facilities. On the other hand, universities have also bet for the future of these techniques as it can be observed in the increase of research publications and doctoral thesis in this field. To reflect this trend a search in different databases was carried out. It is necessary to mention that this search is not comprehensive but it can reflect the evolution of publications in time.

A first search was carried out on the Web of Knowledge using the keywords “remote sensing” as "topic" and “Spain” as "address". This last keyword allows finding publications with at least one author belonging to a Spanish organisation. Counting the number of publications per year that appear in the results of the search it can be observed an increase of publications, especially in the last years. The first work was published in 1983 and was related to the remote thermal sensing (Bolomey et al., 1983). Since then, especially since 1997, the number of publications has been increasing (Fig.5).

If it is compared the number of publications in Spain until now (March, 2012) with other European countries it can be observed that although, far from countries such as Germany, France or Italy, Spain contributes in a greater extend to the scientific production in this field (Fig.6). However, if European data are compared with United States, which presents 17594 of publications using the same keywords, the difference is quite considerable.

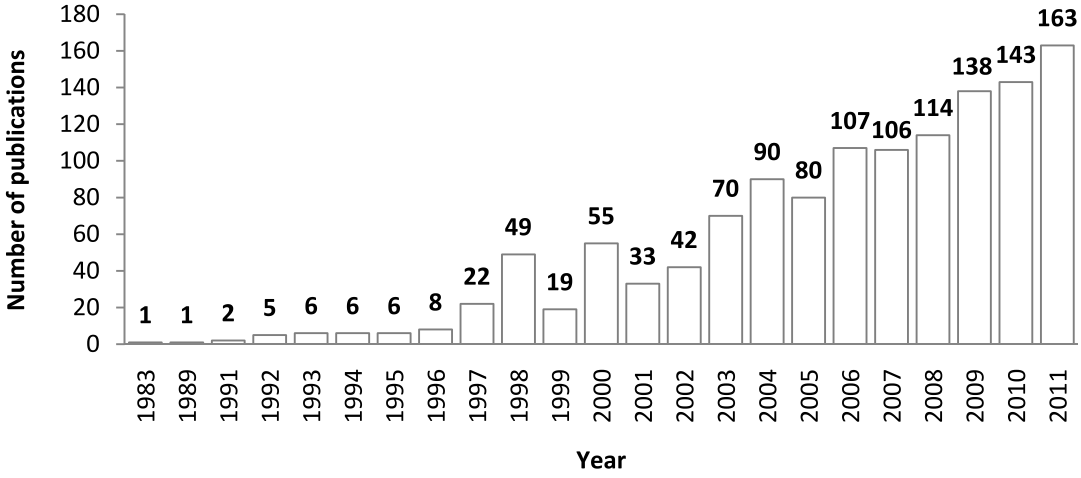

Fig. 5. Number of publications on the Web of Knowledge using the keywords "remote sensing" as topic and "Spain" as address.

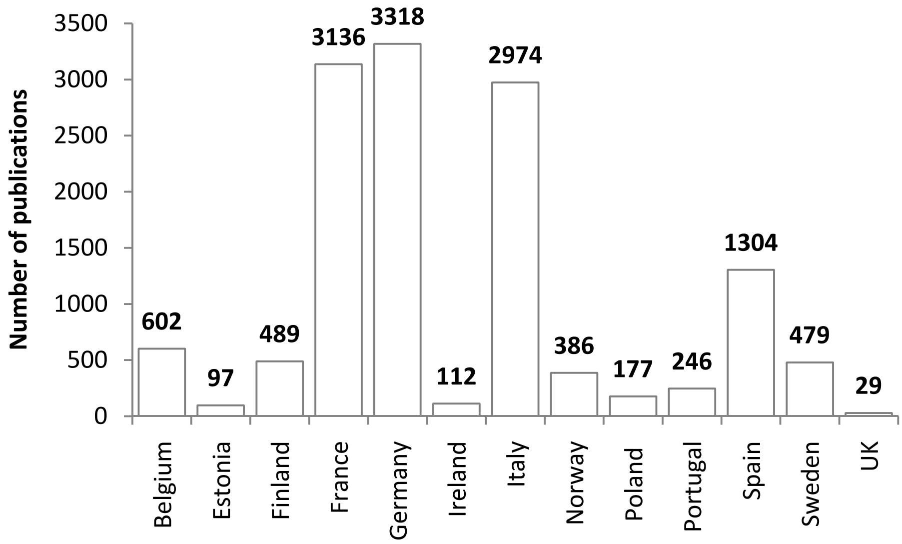

Fig. 6. Search on the Web of Knowledge for different European countries using the keywords "remote sensing" as "topic" and the different countries as "address".

Regarding the thesis defended in Spain related to remote sensing, a search in TESEO database was carried out using the keywords "*teledetección*", "*percepción remota*" and "remote sensing" in title and abstract. The result of this search follows the same trend that the publication of scientific papers. The number of defended thesis in Spain has been increasing over the years (Fig.7). This fact reflects that Spanish universities and research institutes are including remote sensing in their research lines each time more. The first thesis was defended at Universidad Autónoma de Madrid (Autonomous University of Madrid) in 1979. Since then, each year new thesis were appearing with a remarkable increase in the period between 1991-1993 and 1994-1996. 43 out of 76 Universities present in Spain have presented thesis related to remote sensing. The Universities that contribute in a great extend to this field are

Universidad de Alcalá (University of Alcalá) (29 thesis), *Universidad Politécnica de Cataluña* (Polytechnic University of Catanolia) (27), *Universidad de Valencia* (University of Valencia) (24 thesis) and *Universidad Politécnica de Madrid* (Polytechnic University of Madrid) (23 thesis). Regarding Galician Universities, at the *Universidad de Santiago de Compostela* (University of Santiago de Compostela) have been defended up to now 9 thesis whereas at the *Universidad de Vigo* (University of Vigo) have been defended 5. However, in TESEO database no thesis defended at *Universidad de A Coruña* (University of A Coruña), using these keywords, has been found.

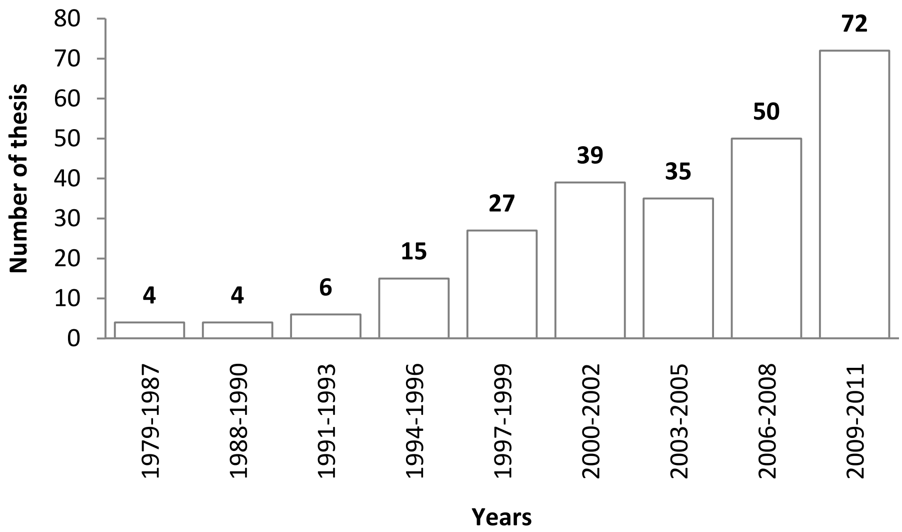

Fig. 7. Number of thesis defended at Spanish Universities from 1979 to 2011. The data presented in this graphic were gathered from TESEO database using the keywords "teledetección", "percepción remota" and "remote sensing".

These data reflect the increasing interest that remote sensing is provoking in Spain. Public and private organisations are investing in this field which results in the apparition of every time more applications and products. This background makes Spain a competitive country at the international level and this situation is expected to continue in the future.

3. Characteristics of remote sensing sensors

3.1 Sensor types

There are different classifications for remote sensing sensors. However, only two broad classes, regarding their way of receiving energy, are mentioned here: passive and active.

- Passive

Passive sensors are defined as remote sensing systems which measure the electromagnetic energy from the Earth surface, not only the reflected energy from the Sun but also the energy emitted for its own temperature as long as the amount of energy is large enough to be recorded. The electromagnetic spectrum wavelengths easily pass through the atmosphere, while other types do not. The ability of the atmosphere to allow energy to pass through it is referred to as its transmissivity, and varies with the wavelength/type of the radiation.

Most of the sensors for environmental purposes belong to this category. Some examples would be MERIS, Landsat, SPOT, PROBA or IKONOS from spacecraft platforms or CASI, AVIRIS or AHS from aircraft platforms. The sensors used in this thesis are passive sensors and be explained more in detail in the following chapters.

- Active

On the other hand active sensors emit their own signal towards a target and detect the backscatter. This kind of sensors lets obtain measurements without depending on the time of the day, the weather conditions or the season. Active sensors can be also used for examining wavelengths that are not sufficiently provided by the sun, such as microwaves, or to control better the way a target is illuminated. Some well-known examples of this kind of sensors are radar (*radio detection and ranging*) and LIDAR (*Light Detection and Ranging or Laser Imaging Detection and Ranging*).

Radar was developed to use radio waves to detect presence of objects and determine their distance and their angular position. The process entails transmitting short bursts, or pulses of microwave energy in the direction of interest and recording the strength and origin of “echoes” or “reflections” received from objects in its field of view (Lillesand et al., 2004). Radar systems may be ground based or mounted in aircraft or spacecraft. Radar remote sensing was first used with military purposes but then civil applications have been at length recognised. Some applications of Radar images in marine environments could be the monitoring of waves, ice or spills. It was well-known the Envisat’s ASAR images over the Galician coast showing the oil spill from the tanker Prestige in November 2002.

LIDAR transmits pulses of laser light toward the ground and measures the time of its return. The return time for each pulse back to the sensor is processed to calculate the distances between the sensor and the various surfaces present on (or above) the ground (Lillesand et al., 2004). One of the most successful applications of LIDAR was the determination of accurate bathymetries but it has applied with success in many fields such as the creation of DEM, mapping vegetation canopy or geological studies.

3.2 Sensor resolution

In remote sensing the term resolution could be defined as the smallest difference between two targets that could be detected by the sensor. This differentiation is referred to a simple determination of the presence of the object (detection) or a precise delimitation of its borders (identification) (Chuvieco, 2008). The second issue requires higher spatial resolution than the first one (Robin, 1998). An object can be detected by its effects in the global observed radiance (e.g. the increase in temperature by a volcano eruption). However, to be identified in detail it is necessary that the minimum feature that the system can detect is much smaller than the object to be identified (Chuvieco, 2008).

It is necessary to consider that the "detailed information" is referred not only to the spatial detail but also to the band number and width, to the temporality and its ability to difference variations in the detected energy (Campbell, 1996). Thus all, spatial, spectral radiometric, temporal and angular resolutions should be considered in remote sensing.

- Spatial resolution

The term is referred to the size of the smallest feature that can be detected in an image. Spatial resolution of passive sensors depends primarily on their Instantaneous Field of View (IFOV). The IFOV can be defined as that area on the ground which is viewed by the instrument at a given altitude and time. Instead of this definition is common to use the pixel size *d* to refer the spatial resolution. The relation between IFOV and pixel size is defined as:

$$d = 2 \cdot h \cdot tan\ (IFOV/2)$$

where *d* corresponds with the pixel size and *h* corresponds with the distance between the sensor and the surface. This area on the ground determines the maximum spatial resolution of the sensor. Images where only large features are visible are said to have coarse or low resolution. In fine or high resolution images, small objects are detected. The spatial resolution depends on several factors such as the orbital height, the focal length and the number of detectors. The spatial resolution of Earth observation sensors ranges between 200 km of pixel size in meteorological satellites (e.g. Meteosat) and centimetres in some airborne sensors (e.g. CASI or AISA).

- Spectral resolution

The spectral resolution is referred to the number, width and position of the sensor spectral bands. It could be said that a sensor will be more suitable when a high number of bands is present. This issue makes easier the spectral characterization of the different surfaces. Regarding the number of spectral bands remote sensing sensors can be divided into three groups: panchromatic, multispectral and hyperspectral. Panchromatic sensors have only a wide spectral band while multispectral systems commonly collect data into three to six spectral bands. On the other hand, hyperspectral sensors acquire images in a high number of contiguous and narrow spectral bands producing much more detailed spectral data. These bands can cover wavelengths from the visible to the shortwave infrared region as well as the thermal infrared region.

- Radiometric resolution

This term is referred to the sensor ability to detect variations in the spectral radiance. The radiometric resolution of an imaging system describes its ability to discriminate very slight differences in energy. The finest radiometric resolution of a sensor corresponds to the sensitivity to detect the smallest difference in reflected or emitted energy. Radiometric resolution can be measured in bits or levels. For example SPOT satellite presents a radiometric resolution of 8 bits (2^8) that corresponds to 256 levels or digital numbers (DN), CASI or AISA present 12 bits (2^{12}) whereas IKONOS and Quickbird present 11 bits (2^{11}).

- Temporal resolution

The temporal resolution corresponds with the frequency of dates of successive images acquisition for a given point on the ground. The cover cycle is related to the orbital characteristics of the platform (height, speed and inclination). It is necessary to take into account that atmospheric conditions limit the acquisition of images taken by optic and thermal sensors. This issue is especially important in zones with high presence of clouds. The revisit time may be measured in minutes (e.g. Meteosat provides an image every 30 minutes) or in days (e.g. Landsat provides images of a same zone every 16 days).

- Angular resolution

This term could be defined as the ability of the sensor to observe the same target from different angles. Several instruments designed specifically for multiangle observation at visible and shortwave infrared wavelengths have already acquired data around the Earth. Some of them are the ATSR-2 (Along-Track Scanning Radiometer-2) launched in 1995 aboard the European Remote Sensing satellite (ERS-2) that provides images at nadir and with an angle of 55˚; POLDER (POLarization and Directionality of Earth Reflectance) installed on ADEOS (Advanced Earth Observing Satellite) and launched in 1997 which can take images in angles of ±43˚ and ±51˚ or The MISR (Multiangle Imaging Spectro-Radiometer) located in the Terra platform since 1999 which obtains images in nine angles with almost simultaneous observations. This resolution is especially useful to map targets located in steep slopes, the canopy structure or to estimate atmospheric variables.

3.3 Remote sensing platforms

A large variety of platforms are available to take remotely sensed data. Since the tethered balloons, used many years ago, new advanced platforms have been developed. These platforms could be divided into two broad groups: spaceborne and airborne.

- Spaceborne platforms

This kind of platforms is operated in the space and corresponds, in a broad sense, with the satellites. Regarding their weight they can be divided into: nanosats (1-10 kg), microsats (10-100 kg), minisats (100 to 1000 kg) or satellites (>1000 kg). A satellite in orbit around the Earth follows an elliptical path which is defined by its altitude, period, inclination and equatorial crossing time. Regarding the orbit, satellites can be divided into geostationaries or heliosynchronics.

A geostationary or geosynchronous satellite presents an equatorial orbit around 36000 km of altitude. Its orbital period is the same as the Earth's for this reason the satellite appears always at the same relative position with an orbital period of 24 h. The geostationary orbits are commonly used by meteorological satellites. On the other hand, a heliosynchronic or sunsynchronous satellite presents a special case of polar orbit with a height range from 600 to 900 km. Like a polar orbit, the satellite travels from the North Pole to the South Pole and always crosses the equator at the same local sun time. This issue allows observing a different area in each moment. This orbit is the most common in the environmental satellites such as Landsat, SPOT, IKONOS, etc.

Spaceborne remote sensing provides frequent and repetitive coverage of large areas. This issue has an effect on a relatively low cost per unit of coverage area. However, the relative low resolution in comparison with airborne images could be a limitation for some studies.

- Airborne platforms

In airborne remote sensing, downward or sideward looking sensors are mounted on an aircraft to obtain images of the Earth's surface. This aircraft can be a Manned Aerial Vehicle (MAV) such as a plane or a helicopter or an Unmanned Aerial Vehicle (UAV) such as platforms remotely controlled. In the last years, the UAV have gained importance in the environmental science due to its advantages with regard to conventional airborne platforms. UAV platforms are believed to be particularly well-suited to missions that are dull (i.e. repetitive and long duration operations extending beyond pilot duty-cycles) and in contaminated or dangerous environments (i.e. extreme environments) (Mackenzie et al., 2009).

In general, an airborne system can provide considerably high spatial resolution data (1 m or less) and the system can be used when atmospheric (i.e., cloud-free), environmental and solar conditions are acceptable to study a specific phenomenon (Myers and Miller 2005). The deployment can also be coordinated with a field program to acquire in situ measurements for instrument calibration, algorithm development or validation. On the other hand this flexibility of user-defined deployments provides a capability to study short time (hours to days) coastal events such as algal blooms, spills or floods that are usually difficult to study. However, its coverage area is usually low and the cost per unit of area, in comparison with spaceborne sensors, is high.

4. Passive remote sensing of aquatic environments

In order to use remote sensed data for the study and understanding of costal aquatic ecosystems, it is important to determine the relationship between the behaviour of light in the water and the reflectance characteristics of benthic components. One of the most commonly cited difficulties in remote sensing of underwater environments is the confounding influence of variable depth on bottom reflectance (e.g. Crackwell et al, 1987). Consequently, the most important characteristic to consider a sensor for mapping benthic habitats is its ability to penetrate into the water to obtain signal from the seabed. Therefore, only the sensors with wavebands in the visible portion of the electromagnetic spectrum are useful for submerged feature detection (Holden and LeDrew, 1998).

The maximum depth from which the sensor receives any significant signal depends on the wavelength and water clarity. Absorption by the water itself limits the depth of penetration for longer wavelengths, whereas absorption by dissolved organic matter and phytoplankton limit penetration at wavelengths shorter than 480 nm (IOCCG, 2000). The variation of spectral attenuation with depth is a key issue for using remote sensing data to determine bathymetry or bottom characterization. The depth and the spectral range of penetration vary greatly as a function of water clarity. Thus, in typical coastal waters, the bottom can be detected until around 30 m while in highly turbid waters, such as rivers with a high suspended sediment load, the depth of light penetration is less than a metre for all wavelengths (IOCCG, 2000). In this case the bottom could not be visible at all.

In order to a sensor could register the signal from the seabed, signal has a complex way to travel. Thus, the downwelling photon flux from the sun must firstly interact with the atmosphere, passes through air-water interface and subsequently interacts with the water column until reaching the seabed. Besides, once the photon flux has interacted with the seabed, it is necessary that retraces its path in a signal strong enough to be recorded by the sensor. A sketch of this process is shown in the Fig. 8.

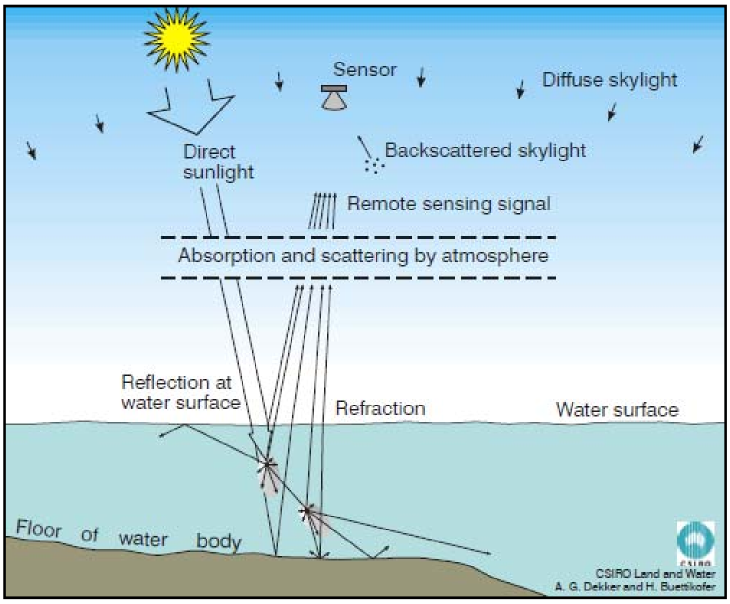

Fig. 8. Processes that contribute to the signal measured by a remote sensor in the coastal zone (Figure taken from Dekker et al. 2001).

The atmospheric contribution and specular reflection at the sea surface constitute noise in the context of benthic mapping and they need to be corrected. In the case of aquatic remote sensing, the total signal received at the sensor altitude is only 8% to 10% of the signal corresponding to the water reflectance (Gordon and Morel, 1983). For this reason, atmospheric correction of coastal imagery inevitably leads to large uncertainties in the retrieved water constituents, as the water leaving radiance (the ‘‘useful’’ signal) is very low compared to the (perturbing) atmospheric ‘‘fingerprint’’ (Mélin and Zibordi, 2005).

The behaviour of electromagnetic radiation in the water column, once it has travelled through the atmosphere depends greatly on the water type. Regarding their composition marine waters can be divided into Case I and Case II waters (Morel and Prieur, 1977; Gordon and Morel, 1983). Case I waters are those waters in which phytoplankton (with their accompanying and derivative material) are the principal agents responsible for variations in optical properties of the water (IOCCG, 2000). On the other hand, Case II waters are influenced not just by phytoplankton and related particles, but also by others substances, that vary independently of phytoplankton, such as notably inorganic particles in suspension and yellow substances (IOCCG, 2000). Thus Case I waters represent ocean waters while Case II waters represent coastal waters. In addition, if the bottom reflectance influences significantly the water leaving radiance signal, water is also considered to be Case II (Dekker et al. 2001). Near the coast, wave action or human influence (e.g. effluence, boating and fishing) adds suspended particulate matter increasing the water optical complexity, making difficult to map the benthic habitats using remote sensing methods.

The subsurface light field in shallow water is not only a function of the properties of the water mixture, but also of the depth and properties of the bottom. Depending on water depth and benthic optical properties, light intensity might decrease more rapidly than expected, remain constant throughout the water column, or even increase with depth (Maritorena et al., 1994). Thus, to interpret data provided by remote sensing sensors it is necessary to introduce some basic notions about the behaviour of electromagnetic radiation in the air-water interface and in the water itself.

4.1 Light and air-water interface

Light as electromagnetic energy, occurs in indivisible units referred to as quanta or photons. Electromagnetic radiation, despite its particulate nature, behaves in some circumstances as it has a wave nature (Kirk, 1994). Every photon has a wavelength, λ, and a frequency, v . The energy, *e*, in a photon varies with the frequency, and inversely with the wavelength. This relation is defined by the expression e= hv, where *h* corresponds with the Planck's constant ($6.63 \cdot 10^{-34}$Js).

When electromagnetic radiation finds a denser media the wave decreases its velocity and in consequence changes its direction. The decrease in the speed of light in the water is ruled by the index of refraction, *n* (λ), defined as the ratio of the speed of light at wavelength λ in a vacuum to the speed of light at wavelength λ in that medium (Bukata et al., 1995). The process is known as refraction and it was firstly described by Willebrord Snel. Snell's Law describes the change in speed and the relationship between the angles of incidence and refraction of a light field as it passes from one medium to another.

$$n_a \cdot \sin\theta_a = n_w \cdot \sin\theta_w$$

Where n_a and n_w represent the refraction indices of air and water respectively, and θ_a and θ_w the angles of incidence (in air) and refraction (in water). This Law affirms that the relation between the incident beam and the refracted one is inversely proportional to the relation between the refraction indices. Thus, light that travels from air to water is refracted due to the differences in the optical density of the two mediums or even reflected back to the atmosphere. The refractive index of air can be assumed to be 1 whereas water, at a temperature around 20˚C, has an index of 1.33.

Years later, Augustin-Jean Fresnel increased the knowledge about this process. Fresnel's equations describe not only the angles and refraction indices but also the wavelength amplitudes when they pass by different media. Thus the Fresnel's equations determine completely the direction of propagation of the reflected and transmitted electromagnetic radiation based on the incident one.

The angle of refraction in water (θ_w), is itself determined by the angle of incidence in air (θ_a) and the refractive index. The percentage of reflectance from a flat water surface shows very low values at zenith angles lower than 50˚, however at higher angles the percentage of reflectance rises very fast (Kirk, 1994). In natural environments it is very unlikely to find water surface as a flat surface. Wind action roughs water surface involving an effect on the sunlight reflectance. Roughening of the water surface by wind has little effect on the reflectance of sunlight from high solar elevations. On the other hand, at low solar elevations reflectance is significantly lowered by wind since the roughening of the surface on average increases the angle between the light direction and the surface at the point of entry (Kirk, 1994) (Fig.9).

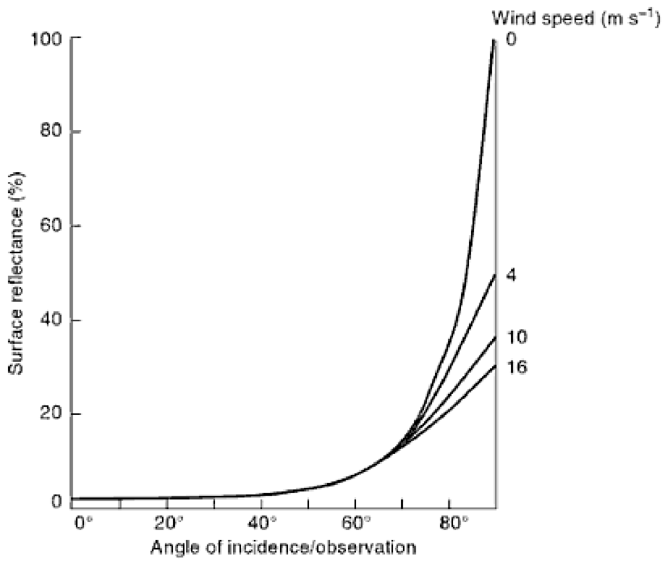

Fig. 9. Reflectance of water as a function of zenith angle of light at different wind speeds (data of Gordon, 1969; Austin, 1974) (Figure taken from Kirk, 1994).

In remote sensing an especial reflection effect known as sun glint need to be mentioned. This effect can be produced when the remote sensor and sun are in the same angle regarding the water surface, and it can be accentuated by wind. Sun glint is a serious confounding factor for remote sensing of water column properties and benthos (Kay et al., 2009). The degree of glint can be drastically reduced using an appropriate choice of sensor geometry, setting the time of image acquisition to provide a solar zenith angle between 40˚ and 55˚ and close to nadir imaging (Purkis and Klemas, 2011). However, the presence of a little degree of sun glint is unavoidable especially in satellite images where acquisition plans and weather conditions are not controlled by the user.

Besides the processes described above, it is necessary to mention that in the air-water interface an internal reflexion can occur. Photons that have interacted with the water column or seabed must then approach to the air-water interface from below interacting with the water surface. In the case of the upward-directed light beam within the water (θ_w) is greater than 49˚, then all the light is reflected down again by the water-air interface and photons will be lost from a remote sensing point of view.

4.2 Attenuation of light in the aquatic medium

Once the photons penetrate into the water they can be absorbed or scattered by dissolved or suspended materials and by water itself. Absorption processes reduce the intensity of the radiance distribution, while the scattering processes also change the directional character of the radiance distribution. This reduction of the radiance intensity is termed attenuation.

The degree of attenuation will depend on the turbidity degree of the water and is wavelength dependant. At short wavelength (blue) light is attenuated in lesser degree than the longer wavelength (red) light (Purkis and Kelmas, 2011). The attenuation is a very important process in remote sensing due to it forms the basis for the interpretation of remote sensing measurements in the visible region of the electromagnetic spectrum (Bukata et al., 1995).

This attenuation can be treated as an additive consequence of the absorption and scattering processes that occur among the photons and the organic and inorganic materials present in the natural water body as well as with the water itself. This attenuation is described in terms of the total attenuation coefficient c(λ), the scattering coefficient b(λ) and the absorption coefficient a(λ). These characteristics are classified as Inherent Optical Properties (IOP) because their magnitudes depend only on the substances comprised in the aquatic medium and not on the geometric structure of the light field. In the Case I waters the principal agent for variations in the IOP corresponds with phytoplankton while in the Case II, besides the phytoplankton, suspended particulate and dissolved organic matter of aquatic or terrestrial origins take part in this variation and they can vary independently of phytoplankton concentration (IOCCG, 2000).

Under typical oceanic conditions, irradiance decreases almost exponentially with depth. This exponential decrease is characterized by the diffuse attenuation coefficient and explained mathematically by the Lambert-Beer's Law:

$$E(z,\lambda) = E_0 e^{(-K_d z)}$$

where, E_0 are values of downward irradiance just below the surface, z corresponds to the depth in meters and K_d corresponds with the diffuse attenuation coefficient. K_d is classified as an Apparent Optical Property (AOP) (Preisendorfer, 1976) which means that it is influenced by the angular distribution of the light field, as well as the nature and quantity of substances present in the medium. Consequently, K_d, will be time dependent and varies systematically with wavelength over a wide range of waters from very clear to very turbid. The diffuse attenuation coefficient (K_d) for any wavelength or spectral band at a determined depth is defined as (Gordon, 1980):

$$K_d(\lambda, \mathrm{z}) = -\frac{1}{E_d\,(\lambda,\mathrm{z})}\left[\frac{\partial E_d\,(\lambda,\mathrm{z})}{\partial z}\right] \mathrm{m}^{-1}$$

where E_d (z) corresponds with spectral downwelling irradiance at depth z and z pointing downward from the surface. This coefficient of downwelling irradiance $K_d(\lambda,z)$ is of a particular interest because it quantifies the presence of light and the depth of the euphotic zone. Jerlov

(1976) exploited this behaviour of K_d to develop a classification scheme for oceanic waters based on its spectral shape.

The distinction between beam attenuation coefficient, c(λ), and diffuse attenuation coefficient $K_d(\lambda,z)$ is important; c(λ) is defined in terms of the radiant power lost from a single, narrow, collimated beam of photons, while $K_d(\lambda,z)$ is defined in terms of the decrease with depth of all photons heading in a downward direction (Mobley, 1994). Near the coast, wave action or human influence adds suspended particulate matter leading to increase attenuation and K_d values. Conversely, in ocean waters the disturbances are either minimal or non-existent and the water is free and clear of any suspended material leading to lower K_d values (Mishra et al., 2005).

The integration of the downwelling irradiance, K_d (λ,z) over the subsurface depth z is defined as the optical depth, $\zeta(\lambda,z)$.

$$\zeta = K_d \cdot z$$

It can be occur that a specified optical depth could correspond to different physical depths but to the same overall diminution of irradiance. For example, very clear waters are characterized by low values of K_d. On the other hand, very turbid waters are characterized by higher values of K_d. Thus for a given physical aquatic depth z, the optical depth in turbid waters will be numerically greater than the optical depth of clear waters (Bukata et al., 1995). Optical depths of particular interest in the context of primary production are those corresponding to attenuation of downward irradiance to 10% and 1% of the subsurface values: these are ζ=2.3 and ζ=4.6 respectively (Kirk, 1994). This optical depth corresponds with the lower limit of euphotic zone and represents the region in which most significant aquatic photosynthesis processes occur.

5. Mapping benthic macroalgae using remote sensing

The potential use of spectral instruments for mapping eelgrass and macroalgae has been recognized by studies conducted in the past (Haxo and Blinks, 1950; Gitelson, 1992 or Rundquist et al., 1996). However, macroalgae and their properties are not as easily detectable as in the case of terrestrial vegetation due to the presence of a water column that decreases the bottom signal. In coastal waters, spectral scattering and absorption by phytoplankton, suspended organic and inorganic matter and dissolved organic substances restrict the light passing to and reflected from the benthos (Dekker et al., 1992). Thus, a proper understanding of the physical interaction between electromagnetic energy and both the vegetation and its environment, as well as careful application of pre-processing steps prior to the analysis of remotely sensed data are requirements to obtained successful results (Silva et al., 2008).

Benthic macroalgae can be divided into three broad groups with the phylogenetic range of Division that correspond with green (Chlorophyta), brown (Phaeophyta) and red macroalgae (Rodophyta). Each of these groups has characteristic pigments involving different optical properties that could be used for separation between them based on their optical signatures.

All of them contain chlorophyll-a, but the presence of other chlorophylls and accessory pigments is varying (Hedley and Mumby, 2002). Chlorophyll-a has absorption peaks at around 435 and 675 nm (Haxo and Blinks, 1950). Chlorophyta contain also characteristic pigments such as chlorophyll-b that absorbs at around 480 and 650 nm and β-carotene that absorbs at around 427, 449 and 475 nm (Hedley and Mumby, 2002).

On the other hand, Phaeophyta contain chlorophyll-c that has absorption peaks at around 460 and 633 nm (Beach et al., 1997), β-carotene and xanthophylls mainly fucoxanthin that absorbs around 426, 449 and 465 nm (Hedley and Mumby, 2002). Because of the dominance of the accessory pigments these algae are brown in colour rather than green (due to their higher absorption in the green waveband).

Rhodophyta are characterized by the presence of β-caroterene and mainly α-carotene which has absorption peaks at around 423, 444 and 475 nm (Hedley and Mumby, 2002). Red algae contain also biliproteins which are divided into the phycoerythrins, phycocyanins and allophycocyanins. The phycoerythrin has an absorption peak at around 543-568 nm, phycocyanin has absorption peaks at around 553 and 618 nm (Smith and Alberte, 1994) and allophycocyanin at around 654 nm (Hedley and Mumby, 2002). The location of each characteristic pigment absorption peaks can vary slightly from one study to another depending on the measurement conditions (in solvents or in vivo), the physiological state of macroalgae, etc.

The distribution in the space and time of the different benthic macroalgae species is a consequence of their adaptation to an array of factors present in the medium (ecological factors). These factors can be divided into: abiotic and biotic and are described in Llera-González and Álvarez-Raboso (2007) as follows:

- **Abiotic factors**

Light. Algae are photosynthetic organisms and therefore light is essential for their life. This factor affects in different ways according to quantity (light intensity), quality (nature of radiation) or the photoperiod (relative duration of the light periods and darkness) (Cabioc'h et al., 1995). Because of the light-absorbing properties of seawater and the planktonic and detritus material suspended in it, the quantity of light reaching the seabed decreases with the increase of depth. Since plants require light in order to carry out their vital process of photosynthesis, there comes a depth at which there is no longer sufficient light in order to support seaweeds. Green algae mainly absorb the wavelengths which correspond to the red region of the electromagnetic spectrum while the red algae prefer the blue-green wavelengths and brown algae generally absorb intermediate wavelengths. This could explain their vertical distribution; however this theory is not absolute.

Temperature. The average temperature as well as the extreme one of is determinant in the geographic algae distribution. According to the latitude, due to its relation to the seawater temperature, several geographic zones of vegetation can be differentiated (polar, temperate, tropical, etc.). This effect related to the luminosity defines the southern and northern limits of the algae in the oceans. However, the distribution of the seawater temperature not only depends on the atmospheric temperature but also it is altered by the warm and cold currents. In the same geographic zone is also necessary considering the thermal daily or seasonal variations. These variations are more important for algae that live in the tidal range due to their exposure to the atmospheric temperature during low tide.

Substrate. With some exceptions algae need to be settled over a substrate. Due to they do not have a root system, algae need to extract the nutritive elements from aquatic medium. For this reason the chemical nature of the substrate does not have influence on their development. Nevertheless, the physical characteristics such as hardness, surface state (rough or smooth) and overall the division degree of this substrate (rocks, blocks, gravels, sands or mud) play a key role in the algae settlement. The most favourable substrates are the ones formed with hard and rough rocks. This kind of substrates makes easier the algae settlement and provides stability for their development. The substrate formed with unconsolidated elements is not an appropriate medium with the exception of calm environments.

Swell. The water movement is a selective factor regarding the distribution of the different benthic species. In very exposed places those algae provided with a fixing system strong enough to withstand the mechanical impact produced by the battering waves are installed. In the calm zones, where the sediment deposits are favoured, only some species adapted to this kind of substrates could live.

The swell along with currents produce the different water layers mixing, homogenizing the temperature and favouring the circulation of nutritive substances and gases in solution. These circumstances favour the settlement of determined species and limit the settlement of other ones. Even algae that belong to a same species can acquire different physiognomy due to the different hydrodynamic conditions.

Chemical composition of seawater. The seawater is a solution of elements and chemical compounds and its composition in a relatively broad region is maintained constant. However, at a local level, some variations in chemical parameters that have a critical influence on algae distribution can be found.

- **Biotic factors**

Different types of relationships can be established between marine algae and between them and the animals that share the same habitat. These relations can make the development of certain species easier or more difficult. The competitiveness is common between different species. In most of the cases, the origin of this competitiveness is the available space or the search for a specific illumination. However, in some cases invasive algae can be competitive with native species and provoke an alteration in the ecosystem or even species disappearance.

Following Bárbara and Cremades (1993) the joint action of all these factors determines that the algae present three types of distributions: spatial, temporal and vertical.

Spatial distribution (geographic). The influence of some ecological factors (mainly light and temperature) according to latitude causes that each species has a defined distribution area.

Temporal distribution (succession). The variations of the ecological factors along the time (months, years, decades ...) can cause the appearance and disappearance of some species in certain times of the year or the variation of their distribution limits within the time. This results in cyclic changes of the landscape.

Vertical distribution (zonation). The dialy oscillation of the tide and the decrease of light according to depth, determine the appearance of a continuous gradient regarding the medium conditions. The algae are settled in an array of fringes according to their ecological requirements. In this way, the coast can be divided into three zones:

- **Supralittoral Zone**. This zone is not usually covered by water. The supralittoral also includes the area splashed or reached by the spray i.e. the splash zone.
- **Littoral Zone**. It is located in the upper and lower level of spring tides (in Galicia 3-4 m) and therefore will stay total or partially emerged twice a day being totally emerged in low spring tides. This is the zone where ecological factors (desiccation, isolation, temperature, salinity, etc.) act with a greater intensity. The time of emersion makes that the high and low zones were subjected to different intensity of these ecological factors. For this reason, a large number of habitats exist here and becomes the richest zone in number of species. Furthermore, this zone can be divided into three specific horizons: high, medium and low.
- **Infralittoral Zone**. This zone is never emerged even during low tide.

Moreover, according to the exposed degree to the swell the Galician coast can be grouped into three large groups (Barbara and Cremades, 1993) (Fig.10):

- **Exposed Coast**. This coast corresponds with cliffs where the waves beat strongly as occurs in the external parts of the Rías. The waves can reach several meters involving a wide supralittoral zone where a dominance of lichens exists. The littoral zone is characterized by the abundant presence of calcareous algae, resistant to the splash of the waves. *Pterosiphonia complanata* and *Gelidium sesquipedale* are present in the lower littoral. In the infralittoral zone there are abundance of *Laminaria ochroleuca*, *Laminaria hyperborea* and *Saccorhiza polyschides*.
- **Semiexposed Coast.** This type of coast corresponds with zones where the waves break with less strength, for this reason these zones are usually located in the middle part of the Rías. The weaker impact of the swell causes that supralittoral zone is narrower than exposed coast. A marked fringe of *Fucus vesiculosus* is typical in the littoral zone. In the infralittoral are typical the same algae than exposed coast.
- **Sheltered Coast**. This coast is surrounded by big rocks, where wave action is much reduced or corresponds with the inner parts of the Rías. In this latter case the sand and mud sediments are typical as well as the salinity changes due to freshwater supplies from the rivers. In this coast the swell is frequently attenuated and in consequence the supralitoral zone is very narrow. In the littoral zone are typical *Pelvetia canaliculata* and *Fucus spiralis*. The infralittoral is characterized by the disappearance of the Laminariales species present in other coastal types and by the presence of *Laminaria saccharina*. Salinities become to be so low that the previous species are substituted by other ones more resistant. It is the

case of *Fucus ceranoides* and *Enteromorpha intestinalis* that are able to live in the river mouths.

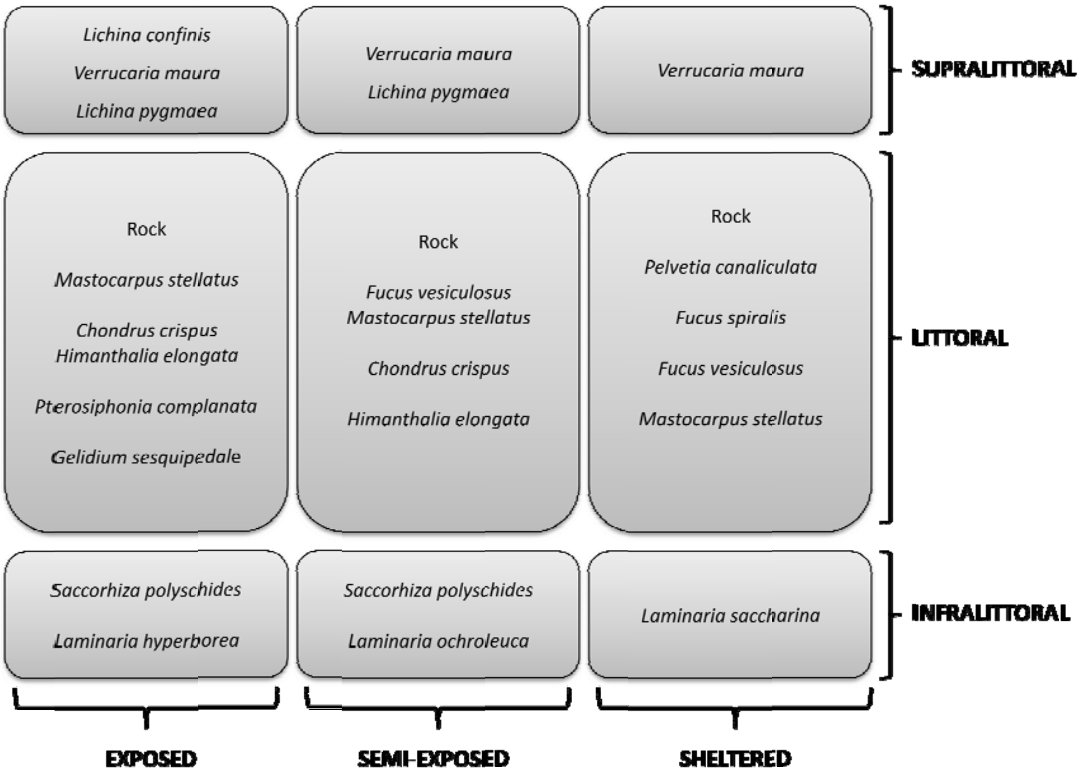

Fig. 10. Types of coast present in Galicia. The different species are adapted to live in certain environmental conditions. This graphic reflects the typical species present in each type of coast and how are vertically distributed (Graphic adapted from Barbara and Cremades, 1993).

In natural conditions macroalgal communities can be found emerged (especially during the low tide) floating or submerged. For this reason their behaviour regarding remote sensing techniques should be considered separately. Concerning submerged vegetation the green region of the electromagnetic spectrum could be considered the most suitable for remote submerged vegetation, followed by the red and red edge regions (Silva et al., 2008). Also the green region provides greater light penetration in waters with higher concentrations of suspended and dissolved material as it occurs in coastal zone (Kirk, 1994). Water strongly absorbs the electromagnetic radiation in the optical spectral region, which results in significant dampening of the radiometric signal. Because of this, reflectance measurements for submerged species are usually very low, on the order of 10^{-1} (Pinnel et al., 2004; Dierssen and Zimmerman, 2003; Fyfe, 2003; Heege et al., 2003). Due to the reduced magnitude of the signal, a careful and adequate correction of atmospheric effects is necessary prior to the analysis of submerged vegetation radiometry derived from airborne and orbital data (Silva et al. 2008).

Remote sensing has been applied in variety of environmental conditions worldwide to map macroalgae communities. For this purpose a high diversity of multispectral and hyperespectral sensors and even bio-optical models are used. In Spain the utilization of remote sensing in the terrestrial zone is well recognised and many studies can be found regarding land cover and land used (e.g. Viedma et al., 2006; García-Ruíz, 2010), burnt areas (e.g. Chuvieco and Congalton, 1989; López-García and Caselles, 1991; Merino-de-Miguel et al., 2010), inland waters (e.g. López-García and Caselles, 1990; Lavery et al., 1993), etc. However, when it comes to mapping shallow benthic habitats the number of studies remarkably decreases. For this reason only a low number of references such as the studies carried out by Fornes et al. (2006) Chust et al. (2010) or Méndez et al. (2011) has been found.

In Galicia the scarcity of benthic mapping studies using remote sensing is more noticeable. Some studies appear in the coastal zone regarding the monitoring of red tides (e.g. Mosquera et al., 2006), oil spills (e.g. Torres-Palenzuela et al. 2006) or upwelling events (e.g. Spyrakos et al., 2011) at a regional scale. However, the only reference found regarding macroalgal mapping was the study carried out by Catoira et al. (1993). These authors performed a preliminary work using multispectral images Landsat 5TM to map macroalgal communities along the Galician coast without significant results. Taken this background into account the work carried out in the present thesis would open a new research line in this study zone.

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OBJECTIVES

OBJECTIVES

In the last years, the Marine Resources and Fisheries Research Group of the University of A Coruña has made a great effort to integrate and complete an array of geographic information from different fields related to coastal environment[37]. In this context the first general objective of this thesis lies in the generation of an infrastructure of georeferenced digital data that can act as cartographic basis for the scientific analysis and management of marine environment.

From this general objective the following specific objectives are derived:

- To digitize a detailed and accurate shoreline for Galician coast. To develop a methodology where the indicator used, its definition and the criteria followed during the drawing were included. To divide the digitized shoreline according to the type of physiographic coastal unit (beach, cliff, marsh, estuary, artificial structures) using dynamic segmentation. The digitized coastline, its derived layers and the methodological protocol will be available for users, establishing the base for a future common and collaborative cartography.

The second general objective lies in the assessment of remote sensing techniques to map macroalgal communities on the Galician coast. The macroalgal communities studied are those which can form homogeneous assemblages larger than the pixel size of the sensors used.

From this general objective the following specific objectives are derived:

- To develop and validate a methodology for mapping intertidal and subtidal kelp forests using images from SPOT-4 (*Satellite Pour l'Observation de la Terre*) satellite.

- To assess the use of CHRIS (*Compact High Resolution Imaging Spectrometer*) sensor to map macroalgal communities and other benthic substrates in the coastal zone, as well as to assess the differentiation among macroalgal groups (green, brown and red).

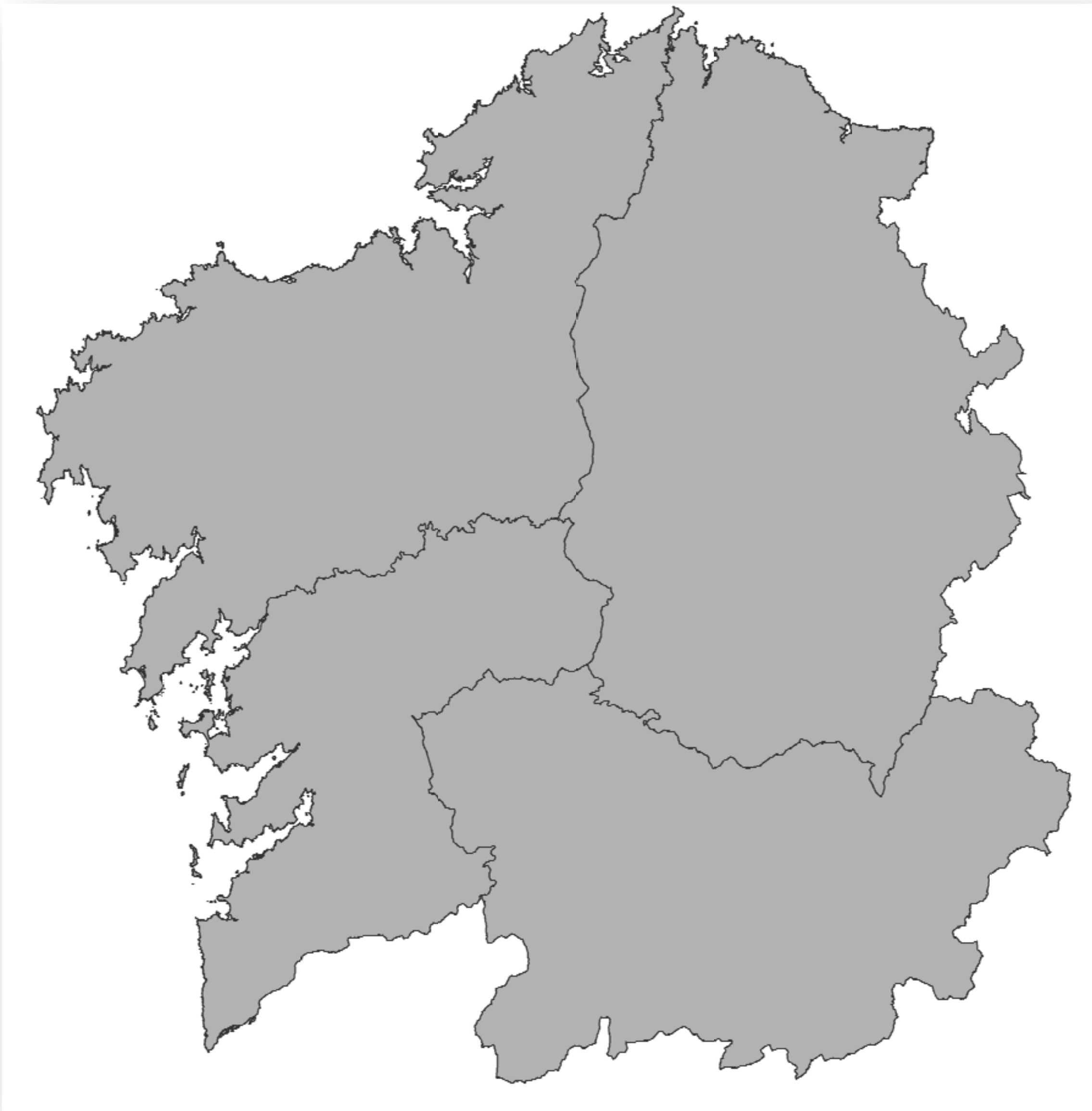
- To assess the use of the airborne sensor AHS (*Airborne Hyperspectral Scanner*) to map macroalgal communities as well as the possible differentiation among the macroalgae groups (green, brown, red) or even species using these images.

- To assess the use of the airborne hyperspectral sensor CASI-2 (*Compact Airborne Spectographic Imager*) to discriminate macroalgal communities by means of a bio-optical model. The spectral separability between macroalgae species will be also analysed and a depth limit for their discrimination established

[37] http://www.recursosmarinos.net/gis last accessed 10 May 2012

- To compare results obtained with the different sensors and establish recommendations for the use of remote sensing methods to study macroalgal communities on the Galician coast.

The chapters of this thesis have been written as stand-alone articles and they can be separately read. For this reason some parts of the contents such as introduction or material and methods can sometimes overlap.



CHAPTER I

CHAPTER I

GENERATION OF A DIGITAL LARGE SCALE SHORELINE OF THE GALICIAN COAST USING PHOTOINTERPRETATION AND DYNAMIC SEGMENTATION

ABSTRACT

The shoreline, defined as the contact limit between emerged and oceanic surface, is a key geographic limit for any study developed in the littoral zone. Although there is a certain degree of consensus in its definition, it gives rise to a multitude of specific criteria for its delimitation depending on the indicator, the source of information used or the digitalization system.

The main objective of the present study was the digitizalization of a shoreline (1:750) of the Galician coast using orthophotographs as geographical base, defining specific digitalization criteria in the process. Moreover, digital layers of geographical information have been derived from the original line and dynamic segmentation has been applied to all digitalized information. Detailed digital and methodological information is available at the URL http://gis.recursosmarinos.net.

Keywords: shoreline, digitizing, GIS, orthophotos, criteria, Galicia.

Based on: Casal G, Sánchez-Carnero N, Freire, J. (2010).Generación de una línea de costa digital de Galicia (NW España) a gran escala utilizando fotointerpretación y segmentación dinámica. Boletín de la Asociación de Geógrafos Españoles, 53:7-19. I.S.S.N.: 0212-9426

1. INTRODUCCIÓN

Cualquier estudio centrado en la zona costera, independientemente de cuál sea su objetivo (gestión del territorio, conservación, construcción de infraestructuras, etc.), requiere el establecimiento de un límite claro entre la tierra y el mar. Únicamente en el ámbito jurídico existe una definición de la línea de costa clara y común a todo el territorio español establecida por la Ley de Costas 22/88, pero la ausencia de unos criterios comunes al resto de las disciplinas que estudian el litoral, provoca la existencia de líneas de costa muy diferentes, aunque no necesariamente excluyentes.

Históricamente, el trazado de la línea de costa ha sido una tarea ardua con importantes limitaciones metodológicas y técnicas, pero hoy en día los Sistemas de Información Geográfica, SIG, nos permiten manejar grandes volúmenes de datos procedentes de diferentes fuentes (fotografía aérea, imagen de satélite, etc.), con diferentes escalas, así como la superposición y actualización de estos datos.

A la hora de trazar una línea de costa utilizando software SIG es fundamental decidir cuál va a ser la definición a seguir. La definición más sencilla es la que entiende la línea de costa cómo la interfaz física entre tierra y agua (Dolan, 1980). No obstante, esta definición no es lo suficientemente precisa ni operativa para ser utilizada en un proceso de digitalización, ya que en ella no se establece qué indicador seguir ni cómo aplicarlo en cada caso, criterios imprescindibles en el trazado junto con la escala de digitalización. La elección de estos parámetros depende del tipo de datos con los que se vaya a trabajar (imágenes de satélite, fotografía aérea, imágenes de video,…), así como de su resolución espacial. La complejidad de este proceso queda patente en el trabajo de Boak y Turner (2005) donde afirman que la digitalización de una línea de costa supone un gran desafío, por lo que es necesario desarrollar una técnica sólida que permita la detección de las características elegidas dentro de las fuentes de datos utilizadas. En este trabajo los autores publican una revisión de estudios de digitalización de líneas de costa, donde recogen las diferentes metodologías, y mencionan los indicadores más utilizados: i) la línea alta de marea o “high water line” (HWL) definida como la línea más alta de marea alcanzada en pleamar, ii) el promedio de marea alta o “mean high water” (MHW) determinado por la intersección del perfil de la costa con una elevación vertical específica, en este caso el promedio de marea alta en la zona de estudio, recogido durante un periodo de tiempo normalmente de 19 años (Feedman y Higgins, 2003) y iii) más recientemente se ha introducido una nueva metodología basada en la aplicación de técnicas de procesado de imagen, que extraen aproximaciones de la línea de costa mediante la utilización de indicadores generados a partir de métodos estadísticos aplicados a imágenes digitales, y no necesariamente visibles para la persona que realiza el trabajo de digitalización.

La mayoría de los autores emplean en sus estudios el indicador HWL, pero en ausencia de una metodología común que defina la representación a seguir en el trazado, el modo de interpretar este indicador varía considerablemente de unos estudios a otros. Un numeroso grupo de investigadores (Anders & Byrnes, 1991; Crowell et al., 1991; Smith y Zarillo, 1990, Zhang et al., 2002) utilizando como fuente geográfica fotografías aéreas, interpretan visualmente el indicador HLW como la línea que representa el límite húmedo/seco que marca la línea de marea alta, en otros trabajos (Dolan et al.,1980; Overton et al.,1999) identifican el mismo indicador a través de la diferencia de coloración que marca el límite húmedo/seco producido por el recorrido máximo del flujo de agua procedente de la ruptura de las olas en marea alta, también conocido como límite superior instantáneo.

Teniendo en cuenta esta problemática se definen los siguientes objetivos:

1) Digitalización de una línea de costa detallada y precisa del litoral gallego, empleando un Sistema de Información Geográfica (SIG), que sirva de base cartográfica para estudios científicos realizados en la zona costera paliando la ausencia de una línea de costa detallada en esta comunidad.

2) Desarrollo y publicación de una metodología en la que se recoja el indicador empleado, su definición y los criterios seguidos durante el trazado, resultando útil para futuros trabajos de digitalización. Con el fin de compartir la información generada, la línea de costa digitalizada, las capas derivadas de ésta así como la memoria metodológica, se pondrán a disposición de los usuarios, sentando las bases de una futura cartografía común y colaborativa que pueda ser constantemente actualizada.

3) División de la línea de costa digitalizada atendiendo al tipo de unidad fisiográfica litoral (costa arenosa, costa rocosa, marisma, estuario y estructuras artificiales), utilizando segmentación dinámica, lo que permite una caracterización costera útil para la gestión del litoral, así como mostrar la enorme potencialidad de esta herramienta para dinamizar la información digital.

2. METODOLOGÍA

2.1. Material

Para el trazado de la línea de costa se emplearon las ortofotos del Sistema de Información Xeográfica de Parcelas Agrícolas (SIXPAC) correspondientes a toda la zona costera de Galicia, cedidas por el *Fondo Galego de Garantía Agraria*, FOGGA en aplicación de lo establecido en la "Conferencia Sectorial de Agricultura y Desarrollo Rural" de 3 de Diciembre de 2003. Estas ortofotos han sido restituidas fotogramétricamente a partir de fotografías aéreas tomadas entre agosto y septiembre de 2002 y junio, julio, agosto y septiembre de 2003. La escala de los vuelos fue de 1:18000 y la resolución empleada en su escaneo fue de 14 µm. Las ortofotos finales están corregidas con un modelo digital del terreno de 5 m y presentan una resolución espacial de 0.5 m. Todo el trabajo de digitalización fue llevado a cabo utilizando el programa ArcGis 9.2.

2.2. Métodos

Una vez establecida la información espacial sobre la que digitalizar la línea de costa, se eligió el indicador a seguir para su trazado. En este estudio se optó por utilizar la línea de marea alta o "high water line" (HWL) definiéndola como el límite húmedo/seco e interpretándolo como la línea definida por la diferencia de coloración que marca el retroceso de la marea (la línea de última marea alta) (Fig. 1), siguiendo a autores como Dolan et al. (1978) que consideran este indicador estable y menos sensible al coeficiente de marea que el límite superior instantáneo, donde rompen las olas. Se descartó el uso de otros indicadores apropiados en estudios similares, como los límites entre la duna y la playa alta, habitualmente identificados por la presencia de vegetación (Ojeda, 2000), debido a las características de la costa gallega, donde más del 50% se han visto modificadas con estructuras artificiales y muchas otras se encuentran en zonas de acantilado (según datos del Ministerio de Medio Ambiente). Aunque se ha considerado como la mejor de las opciones disponibles, es necesario tener en cuenta que la línea de costa resultante de este criterio es una aproximación sujeta a variaciones de interpretación, especialmente cuando se digitaliza de forma manual en fotografías aéreas (Moore et al, 2006). Debido a esto, y con el fin de minimizar este error, toda la digitalización fue realizada por una única persona. Valorando la relación de tiempo invertido y precisión obtenida, se estableció la escala de digitalización en 1:750.

Fig.1. Detalle de la playa de Langosteira (Fisterra) donde se observa el trazado de la línea de costa siguiendo el cambio de coloración que deja la marea alta en la arena.

El amplio rango mareal de la costa gallega (entre 2 y 4 m) introduce una significativa variabilidad a la hora de obtener una línea de pleamar homogénea, puesto que cuanto mayor es el rango, mayores resultan las diferencias altimétricas (y por lo tanto, horizontales) de la pleamar en función del coeficiente de marea. Esto haría aconsejable la corrección de aquellas fotografías tomadas en momentos diferentes a la marea alta, pero este proceso fue descartado por tratarse de una zona de estudio muy amplia, aproximadamente 2200 km (según resultados obtenidos en este estudio), dado que el aumento de precisión que se obtendría sería mínimo en relación con el esfuerzo que sería necesario invertir.

En cuanto a los criterios de digitalización, *a priori* se establecieron cinco tipos principales de costa: estructuras artificiales, costa rocosa, costa arenosa, marisma y estuario, para las cuales se definieron criterios de trazado generales (Tabla 1, Fig.2).

Tabla 1. Tipología costera utilizada para la definición de los criterios de digitalización. Las explicaciones detalladas sobre los criterios se pueden consultar en la Tabla 2 y en http://gis.recursosmarinos.net

TIPOLOGÍA	**DEFINICIÓN**	**CRITERIO GENERAL**
Estructuras artificiales	Estructuras que han sido creadas por el hombre (puertos, carreteras, diques, etc.)	Cuando existen estructuras artificiales, fijas y no flotantes, se continúa la línea de costa siguiendo a las mismas
Costa rocosa	Sustrato rocoso: acantilados, escarpados rocosos, playas de cantos, etc.	En acantilados con alto grado de verticalidad el trazado se realiza siguiendo la línea de agua, en zonas rocosas se sigue la línea de la última marea alta
Costa arenosa	Sustrato arenoso	Se sigue la línea de última marea alta, marcado por la línea de transición entre la arena húmeda y la seca
Marisma	Terreno pantanoso inundado por el mar en marea alta	Se sigue el límite de vegetación permanente que marca la zona no inundable
Estuario	Desembocaduras de ríos o corriente de menor caudal susceptibles de ser afectadas por la marea	El trazado de la línea se extiende río arriba hasta donde la altitud de ribera sea menor a 4 m

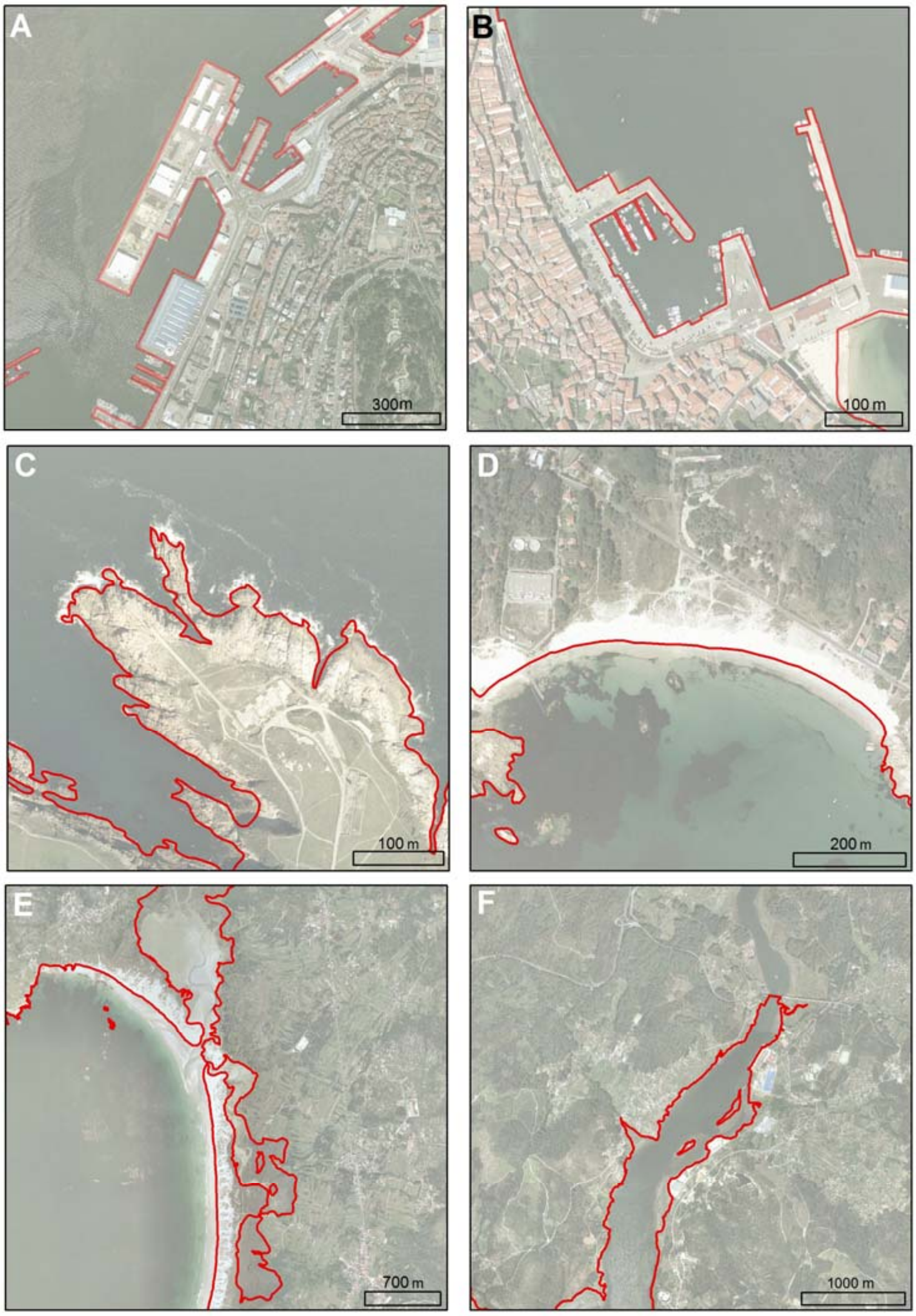


Fig.2. Tipología costera principal recogidas en la librería de criterios. A) Estructuras artificiales. B) Detalle de un puerto. C) Zona rocosa. D) Zona arenosa. E) Marisma. F) Estuario.

Sin embargo, a medida que se avanzaba en el trazado de la línea, la heterogeneidad geomorfológica de la costa gallega obligó a definir nuevos criterios, enmarcados dentro de la tipología inicial (Tabla 2). Todos estos casos fueron incluidos en una librería de criterios y aplicados a la totalidad de la línea, de tal forma que en cada punto del trazado se siguiese un patrón ya establecido, agilizando así el proceso y minimizando el error. En una sexta categoría se incluyeron casos particulares donde se engloban estructuras que no se clasificaban dentro de ninguno de los grupos anteriores y que aparecieron de forma puntual a lo largo del trazado.

Tabla 2. Casos recogidos en la librería de criterios.

TIPOLOGÍA	CASOS DERIVADOS	TRAZADO
ESTRUCTURA ARTIFICIAL	Zona de relleno arenosa	Se siguen los criterios de zonas arenosas
	Zona de relleno arenosa donde el límite húmedo-seco no se aprecia con claridad	La línea discurre a lo largo de la estructura artificial
	Zona de relleno rocosa	Si se diferencia la línea de marea se emplea ésta para continuar el trazado. En caso contrario se sigue el contorno de la estructura artificial
	Estructuras artificiales que no afectan al recorrido de subida y bajada de la marea	El trazado continúa obviando estas estructuras
	Rampas de puertos	Si la situación es de marea alta se sigue la línea de agua. Si la marea es baja siguiendo el límite húmedo/seco
COSTA ROCOSA	Zonas rocosas no acantiladas	Se sigue la línea de última marea alta
	Línea de marea alta no visible	Se sigue la línea de agua
	Ni línea de agua ni de marea visibles	Se sigue el límite terrestre
	Existe alguna duda en el trazado de la línea de marea alta	Se sigue la línea de agua
	Zona rocosa separada del continente por un canal de agua	Se digitaliza como parte de la costa, siempre que este canal no supere una anchura de 5 m. En caso contrario este tramo se considera isla
COSTA ARENOSA	Cuando existen aportes de agua en la zona arenosa	Se sigue el limite húmedo/seco obviando el aporte de agua
	Si existe alguna duda en el trazado de la línea de marea alta	Se sigue la línea de agua

Una vez digitalizada la línea de costa se realizó una división de la misma usando la herramienta de segmentación dinámica disponible en ArcGis 9.2. Esta herramienta permite la visualización y análisis de información lineal segmentada siguiendo diferentes criterios y utilizando límites almacenados en forma de tablas sin la necesidad de dividir el elemento lineal. En este caso la línea de costa fue dividida siguiendo la tipología establecida para su trazado y ya recogida en la librería de criterios (estructuras artificiales, costa arenosa, costa rocosa, marisma y estuario).

Asimismo, para obtener una información más completa se incluyeron en el trazado las islas e islotes presentes en las aguas costeras. Debido a su elevado número en la zona de estudio se estableció un límite de tamaño (15 m en su diagonal mayor) por debajo del cual no fueron digitalizadas. Los criterios seguidos en su digitalización fueron los mismos que los utilizados para la zona terrestre ya recogidos en la librería de criterios.

Finalmente se generaron líneas de costa derivadas a partir de la línea original (variando el detalle, eliminando áreas con determinadas características (zonas de aguas salobres), etc.), adecuadas para su utilización en estudios particulares.

3. RESULTADOS Y DISCUSIÓN

El resultado principal del proceso de digitalización fue la obtención de información geográfica digital referente a la costa gallega, compuesta por varias capas vectoriales y una librería de criterios. La línea de costa digitalizada a escala 1:750 comprende todo el litoral gallego (Fig.3) desde el municipio de Tomiño (41º57.0'N, 8º44.9'W) hasta el municipio de Ribadeo (43º27.56'N, 7º5.0'W) con una longitud total de 2272.22 km incluyendo zonas de agua salobre.

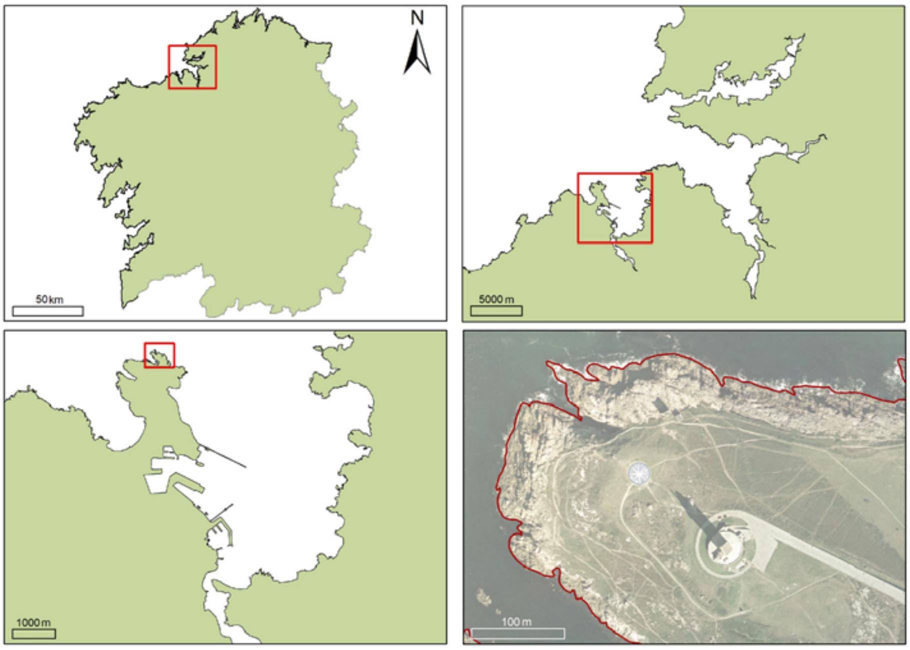


Fig.3. Línea de costa digitalizada presentada a diferentes escalas en la zona de la Ría de A Coruña. En este caso se representa la línea de costa que incluye zonas de agua salobre.

Además de esta línea de costa se obtuvo una capa vectorial con 1127 islas e islotes, que representan a su vez un total de 347.7 km de costa (Fig.4). En esta capa se puede observar la gran heterogeneidad en cuanto al tamaño de las islas presentes a lo largo del litoral gallego (Fig.5). Entre ellas podemos encontrar desde islas con un perímetro de 26.85 km como la Illa de Ons, situada en la Ría de Pontevedra, a islotes de 18.50 m, si bien, el 44.45% se encuentran por debajo de 100 m de perímetro y el 96% por debajo de los 1000 m.

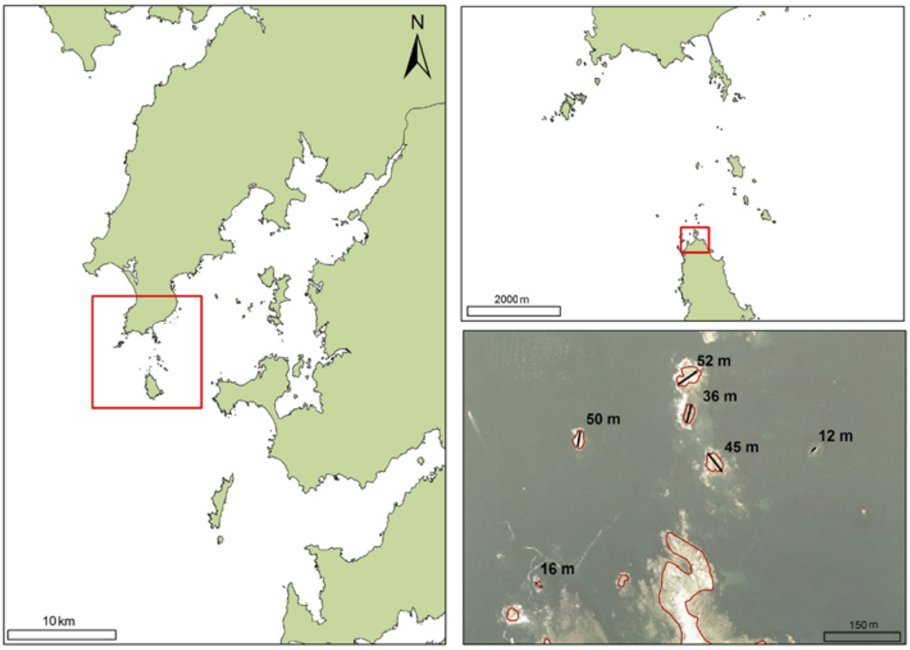


Fig.4. Detalle de la Ría de Arousa a diferentes escalas. En la figura se muestran islas e islotes, indicando la longitud de su eje mayor (m). Sólo se incluyeron en el trazado las que presentaban una superior a 15 m.

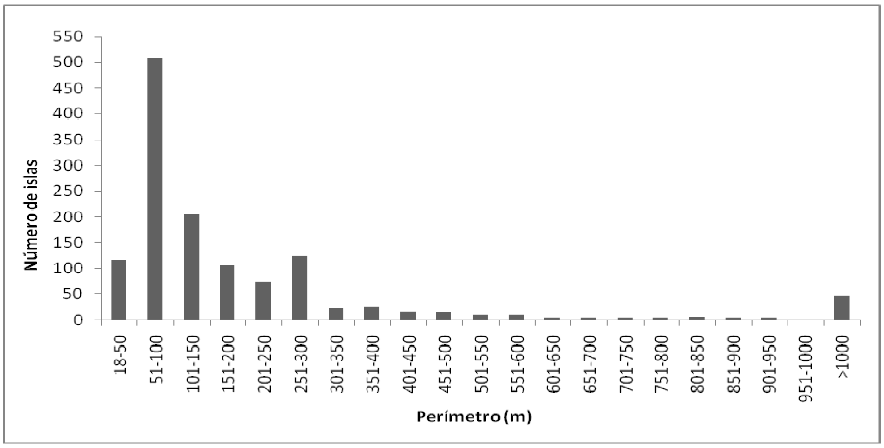


Fig.5. Distribución de frecuencias de tamaño, según su perímetro en m, de las islas e islotes digitalizados en la costa gallega.

Aplicada la segmentación dinámica (Fig.6) se obtuvo una línea de costa dividida en 2565 fragmentos (en función de sus morfologías), con un total de 1365.50 km de zonas rocosas, 246.59 km de zonas arenosas, 389.58 km de estuario-marisma y 269.38 km de sustratos artificiales. Además esta línea presenta 625.5 m correspondientes a la línea de corte utilizada en las bocas de los ríos. Esta línea de costa, además de constituir una herramienta de gran utilizad en la gestión costera, ejemplifica la potencialidad de la herramienta segmentación dinámica en los estudios de ámbito costero.

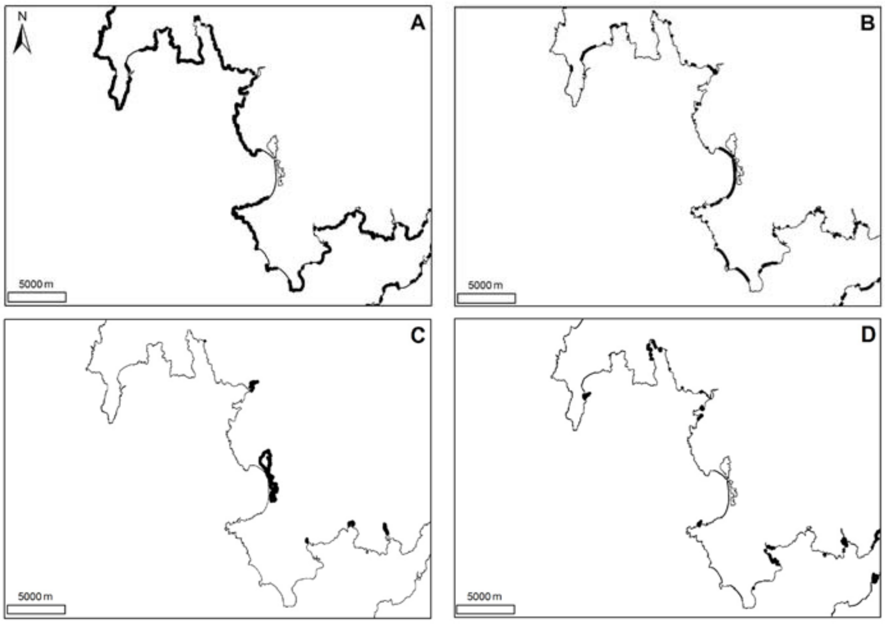


Fig.6. Línea de costa clasificada utilizando segmentación dinámica. Se representa la zona del Seno de Corcubión. En cada figura se resalta un tipo de costa diferente: A) Sustrato rocoso. B) Sustrato arenoso. C) Marisma y estuario. D) Sustrato artificial.

A partir de la línea de costa digitalizada originalmente se obtuvo otra línea de costa que marca estrictamente el límite húmedo/seco dejando fuera lugares de agua salobre (frente costero) con una longitud de 1915.64 km. Por otra parte, se delimitaron las zonas de marisma y estuario presentes a lo largo de la costa (Fig.7). Estas zonas comprenden una superficie total de 5607 ha, entre las cuales se encuentran cinco zonas protegidas: Ría de Ortigueira e Ladrido, Ría de Ribadeo, Complejo intermareal Umia-Grove, Laguna de Corrubedo, Laguna y arenal de Valdoviño.

Fig.7. Zonas de marisma y estuario. Estas zonas fueron delimitadas a partir de la línea de costa que incluía zonas de agua salobre y constituyen una superficie de 5607 ha, entre ellas se encuentran cinco zonas protegidas. A) Marisma de Carnota. B). Marisma de Corrubedo.

En este momento se siguen desarrollando los resultados obtenidos en este estudio realizando análisis de cara a definir el efecto de la escala de digitalización empleada en la longitud de la línea de costa resultante.

Durante la realización de este trabajo se generó una librería detallada, donde se recogen los criterios generales para cada categoría y las variaciones surgidas durante el trazado, así como el protocolo seguido en cada uno de los casos. Aunque es consecuencia del proceso metodológico, este documento constituye en sí mismo un resultado que puede ser el punto de partida para futuros trabajos de digitalización de líneas de costa. El uso de esta librería de criterios permite superar parcialmente la problemática ligada a este tipo de estudios. De ahí la importancia de documentar la metodología seguida y la resolución de los problemas específicos. Su publicación y acceso libre tienen como objetivo ampliar y mejorar los criterios desarrollados en este trabajo, de modo que la creación de nuevas líneas de costa sea coherente empleando criterios definidos y detallados en todo su trazado. Con este trabajo se intenta generar unos criterios unificados, eliminando los grandes errores de cálculo final cuando se trabaja con documentos que utilizan criterios diferentes (Ojeda, 2000). Además de propiciar la creación de nuevas líneas de costa con criterios ya establecidos, al tiempo que se pretende evitar el sobreesfuerzo de volver a crear lo ya existente e invitando a los usuarios a que modifiquen o mejoren esta información.

Todos los resultados de este trabajo, tanto la cartografía digital como la librería de criterios, se encuentran publicados en la página web http://gis.recursosmarinos.net bajo una licencia Creative Commons 2.5, en su opción Reconocimiento-Compartir Igual, con el fin de que los usuarios interesados puedan acceder a dicha información.

A la hora de utilizar estos resultados en futuros trabajos, es necesario tener en cuenta que la posición de la línea de costa varía continuamente a lo largo del tiempo como consecuencia del movimiento de los sedimentos en la zona litoral y especialmente, debido a la naturaleza dinámica del nivel del mar en los límites costeros (olas, mareas, tormentas, etc.) (Boak & Turner, 2005). Por esta razón, este límite debe ser considerado como una estructura dinámica y como tal, sería aconsejable continuar su revisión y actualización con el fin de mantener la precisión de la misma.

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CHAPTER II

CHAPTER II

REMOTE SENSING WITH SPOT-4 FOR MAPPING KELP FORESTS IN TURBID WATERS ON THE SOUTH EUROPEAN ATLANTIC SHELF

ABSTRACT

Remote sensing has become an increasingly used technique for the thematic mapping of large marine areas. In recent years, many researchers have successfully applied these techniques in different places for benthic mapping in clear waters; however, areas with turbid waters present important limitations that are gradually being solved by recent technological advances. In this context, the main objective of the present study is to develop and validate a methodology for mapping intertidal and subtidal kelp forests in the Galician coast (NW Spain), based on images from SPOT-4 (Satellite Pour l'Observation de la Terre). Three analysis methods have been applied: visual analysis and interpretation, unsupervised classification (cluster) and supervised classification (angular classification and maximum likelihood classification). Classification percentages higher than 70% in all substrates were obtained both using visual analysis and interpretation and maximum likelihood classification.

Keywords: remote sensing, multispectral, kelp forest, turbid water, benthic mapping.

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1.INTRODUCTION

Kelp forests play an important ecological role in intertidal and subtidal coastal ecosystems. These forests are essential for many organisms as habitats (Schultze, 1990, Birkett, 1998, Christie et al., 1998, Pallas et al., 2006), mating and nursery grounds (Sjøtun et al., 1993; Schultze, 1990; Borg et al., 1997 and Shaffer, 2003) and feeding areas (Velando & Freire, 1999, Lorentsen et al., 2004). Another relevant aspect is their important contribution to primary production (Mohammed & Fredriksen, 2004), as well as to sediment stabilization and coastline protection (Madsen et al., 2001).

Nevertheless, in recent years a decrease in the extension of these communities has been observed. One of most dramatic cases is that of the “ghost forests” in South California (Parnell et al., 2004), where vast extensions of *Macrocystis pyrifera* virtually disappeared. This decrease has been documented around the world by several authors (Barry et al., 1995; Walther et al., 2002, Hawkins et al., 2003; Parmesan & Yohe, 2003; Britton-Simmons, 2004).

The causes of this degradation are not known, although many studies have addressed them. Authors such as Floc’h et al. (1996) and Viejo (1997) have stated that these populations can be threatened by spatial competition with foreign kelp species, introduced for their exploitation and commercialization. Other authors have demonstrated that these species are vulnerable to pollution (Chung & Brinkhuis, 1986), as well as to the increase in water turbidity (Edwards, 1980). Another possible reason for kelp forest decrease is the increase in sea temperature due to climate change, which may affect the distribution of *Laminaria* species in European waters (Hiscock et al., 2004). Moreover, some kelp communities have been affected by bottom trawling fisheries (Christie et al., 1998).

In Galicia (NW Spain), several species of the Order Laminariales can form great extensions or forests: *Chorda filum, Laminaria hyperborea, Laminaria ochroleuca, Laminaria saccharina* and *Saccorhiza polyschides,* according to the information collected by Bárbara and Cremades (1993) and to distribution studies by Pérez-Ruzafa *et al. (*2003). Recreational divers and fishers have recently warned of the regression and possible disappearance of these kelp forests in this region, particularly in the Southern coast. Although there are currently no studies to confirm this decrease or assess its possible causes, if this fact is confirmed it could constitute a serious problem, given the essential role these habitats play in the life cycle of many commercial species and the importance of the fishing activity in Galicia (Freire and García-Allut, 2000).

Remote sensing has become an increasingly used technique for mapping large areas, both terrestrial and marine, due to the important advantages it provides with respect to direct observation methods: it is less costly both in terms of time and funding, requires less human effort, provides wide time series datasets and provides information in the non-visible region of the electromagnetic spectrum. In recent years, many researchers have successfully applied these techniques in different locations for benthic mapping in clear waters (Hochberg and Atkinson, 2000, 2003; Karpouzli et al., 2004; Kutser et al. 2006; Bertels et al., 2008). For turbid waters, although there are some experiences with positive results such as those obtained by Simms & Dubois (2001) in the Atlantic coast of Canada, and Vahtmäe and Kutser (2007) in the

Estonian coast, there are important limitations, derived from the poor wavelength penetration into the water. These limitations are gradually being solved by recent technological advances in this field.

In this context, the main objective of the present study is to develop and validate a methodology for mapping intertidal and subtidal forests of Laminariales in turbid waters, using the Galician coast as a case study, based on satellite images from SPOT-4 (*Satellite Pour l'Observation de la Terre*). It is worth noting that this work constitutes a first methodological assessment for the prospective and retrospective monitoring of these habitats, which could be further developed in the future with the use of more advanced sensors.

2. MATERIALS AND METHODS

2.1 Study area

The study area includes the Seno de Corcubión, located in the Northwest of the Galician region. Its northern limit is constituted by Cape Fisterra, while its Southern limit is the Ria de Muros e Noia (Fig. 1). The study was carried out along 113 km of coastline, covering a total area of 4089 ha between the coastline and the 10 m isobath. The establishment of this external limit was based on the light penetration values in the water column in this area according to previous work.

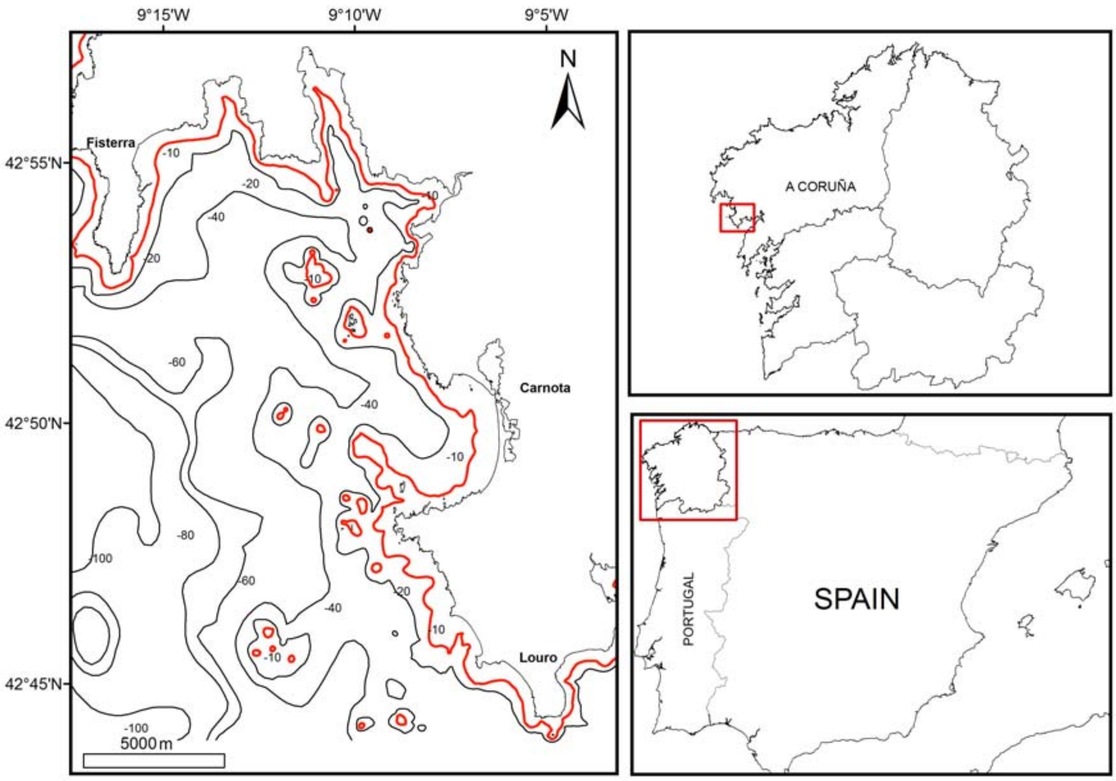

Fig.1. Study area: Seno de Corcubión (Galicia-NW Spain). The study area covers the stripe between the coastline and the 10 m isobaths (red line

2.2 SPOT images

Two images from satellite SPOT-4 were used: one from 2006 and one from 2008. Both images correspond to summer months, when seaweeds of the Order Laminariales reach higher growth rates and sizes. The best timing for image acquisition would be during low tide, although this aspect is limited by the frequency of satellite pass over the study zone. In fact the 2006 image was taken in low tide whereas the 2008 image corresponded to high tide.

The image corresponding to summer 2006 was acquired through the OASIS (*Optimizing Access to SPOT Infrastructure for Science*) program in multispectral mode with a spatial resolution of 20 m. The image from August 2008 was acquired through the "ESA Category-1 scheme" [38] program; this image has a spatial resolution of 20 m and is divided in two fragments successively taken (11:39:57, 11:40:03 UTC). Both images were acquired in 1A pre-processed level (i.e. with radiometric correction), and subsequently georreferenced. Both have less than 25% cloud cover; however, the 2008 image was taken during unfavourable wind conditions for bottom visualization.

For this study, XS1 (500-590 nm), XS2 (610-680 nm) and XS3 (780-890 nm) bands of the multispectral image were used, due to their coincidence with the most representative reflectance peaks of the spectral signature of Laminariales, according to authors such as Augenstein et al. (1991), Chauvaud et al. (2001) and Pascualini et al. (2005).

2.3 Orthophotographs

Given the impossibility of sampling simultaneously to the image from 2006 since its date was previous to the start of the study, the establishment of training polygons for each of the studied substrates was done through the use of orthophotographs from SIXPAC (Geographical Information System devoted to the monitoring of agricultural activity within the Common Agrarian Policy) corresponding to the study area; these were provided by the *Fondo Galego de Garantía Agraria* (FOGGA) dependent of the *Consellería de Medio Rural* of Autonomous Galician Government. These orthophotographs were restituted photogrammetrically from aerial photographs taken in the months of August and September 2002, June, July, August and September 2003. The flight height and a scanning resolution of 14 μm allowed obtaining photographs with a scale of 1:18000. The resulting photographs were orthocorrected to a 5 m digital land model and showed a resolution of 0.5 m.

2.4 Direct observations

With the aim of validating the results obtained through the processing of the image from 2008, direct observations were carried out in May and August 2008. These observations consisted of 8 diving transects (100 m long each) distributed across the study area in those zones where kelp beds were expected to occur (Fig. 2). Substrate type and relative abundance of

[38] http://eopi.esa.int/esa/esa?cmd=aodetail&aoname=cat1, accessed by December 2009

Laminariales were visually registered along these transects, codified according to a scale from 0 to 3 (absent, disperse, medium or abundant).

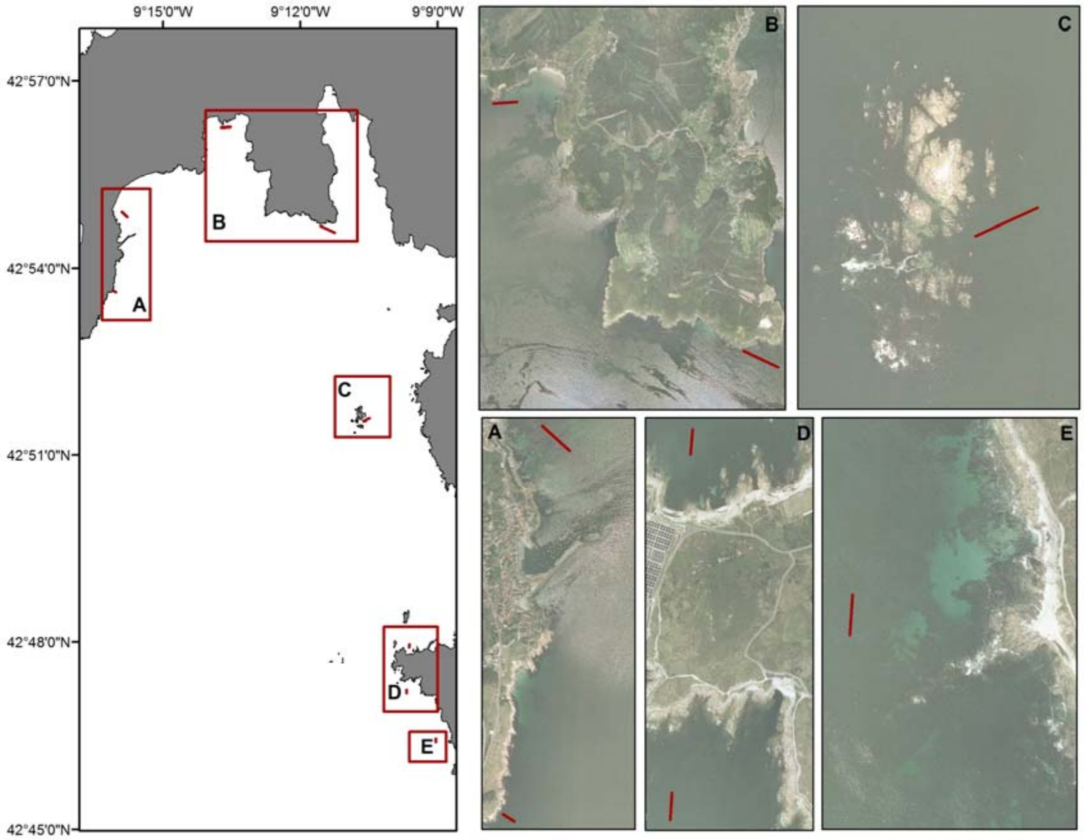

Fig.2. Diving transects (red lines) carried out in summer 2008. Eight transects were carried out, each one 100 m long, in areas where the classification performed on the image from 2006 showed presence of kelp beds.

Due to the impossibility of carrying out observations simultaneously to image capture, additional information was collected from recreational divers and commercial fishermen that frequently visit the area. The information collected consisted of 10 delimited zones on printed maps where the presence of kelp beds was identified.

2.5 Data analysis

To assess the performance of different methods for kelp forest mapping in turbid waters, SPOT images were subject to 2 types of analysis: unsupervised classification (cluster) and supervised classification (angular supervised classification and maximum likelihood analysis), using Idrisi Andes 15.0, ArcGis 9.2 and ENVI 4.6.1 software. Prior to the realization of the analysis, four substrate classes were established: seaweed, submerged sand, emerged sand and emerged rock.

Before analysing the data, and with the aim of eliminating the spectral variability caused by land and marine areas outside the study area, a terrestrial and a bathymetric mask were applied to the images using the Galician coastline (Casal et al., 2010) and the 10 m isobath, respectively. Furthermore, the resulting bands were subject to histogram equalization, increasing contrast among similar values and improving their visualization. Subsequent analyses were performed both on the original and equalized bands.

Both 2008 images were taken as a stereo pair by the two identical HRVIR (Visible & Infrared High-Resolution) optical sensors on board of SPOT-4 having, each of these sensors, different radiometric calibration. The two images showed significant differences in digital levels for areas present in both images (Fig.3) despite having been taken successively (11:39:57, 11:40:03 UTC) for this reason the images were analyzed separately. These differences could be explained by differences in the radiometric calibration of the sensor.

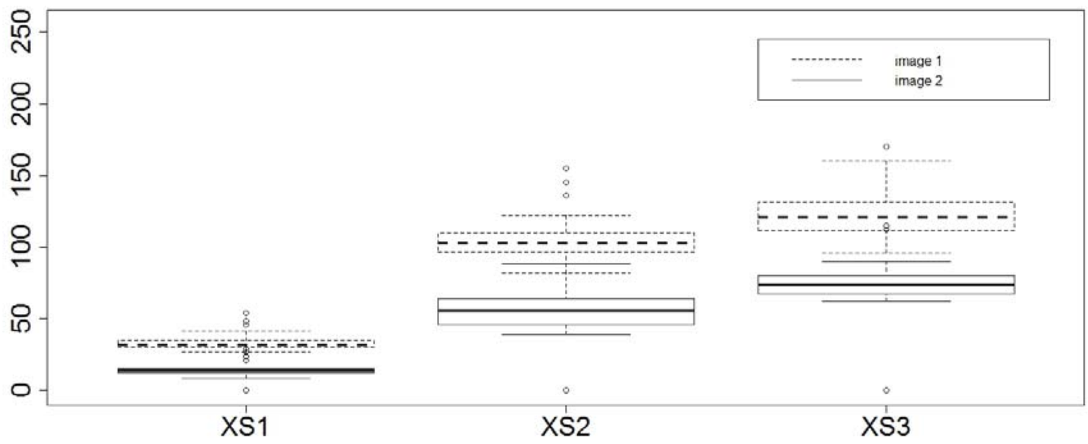

Fig.3. Example of the differences observed between both 2008 images. In this case the differences in the three SPOT bands (XS1, XS2, XS3) for the submerged sand class, common to both images, are represented. Box represents the digital level distribution and the horizontal line represents the median value. Highest and lowest values are represented by the whiskers limits and circles correspond to the outliners.

In a first stage of the analysis, emerged sand, submerged sand, emerged rock and kelp substrates were mapped in the study area through visual interpretation, using a composition of equalized bands for each image. The definition of the class "submerged rock without seaweeds" was not possible using orthophotographs; furthermore, the absence of this substrate in the observation transects carried out in 2008 did not allow for the use of this typology in the analysis for that year. For this reason, and taking into account the experience of the research group in the study zone as well as information from recreational divers and fishermen, all submerged rocky bottoms have been assumed to be covered by seaweeds, since maximum coverage of Laminariales occurs during summer.

2.5.1. Band ratio

Several band ratios, using all paired combinations of bands (XS1, XS2 and XS3), were carried out following authors like Gower et al, 1984; Gower, 1994 and Augenstein, et al. (2001) employing the original bands with land and bathymetric mask.

2.5.2 Unsupervised classification/ Automatic methods

All images were subject to cluster analysis, which allows for the automatic grouping of pixels in different classes as a function of their spectral signature. This cluster analysis uses the histogram peak technique using the algorithm implemented in IDRISI software. This is equivalent to looking for the peaks in a one-dimensional histogram, where a peak is defined as a value with a greater frequency than its neighbours on either side. Once the peaks have been identified, all possible values are assigned to the nearest peak and the divisions between classes fall at the midpoints between peaks (Eastman, 2003). Although the objective of the analysis was to identify 4 spectrally different classes (seaweed, submerged sand, emerged sand and emerged rock), the analysis was performed for 30, 20 and 10 classes. In cases where spectral variability within classes is greater than between classes is recommendable to perform the clustering algorithm for a greater number of classes. For example, digital levels for emerged sand present a variance of 1899 (N=48) while the variance of both classes, emerged and submerged sand analysed together, decrease to 1197 (N=94).

2.5.3 Supervised classification / Semiautomatic methods

Supervised classification methods use training polygons to map the study area for each of these classes. In this case, the definition of training polygons, where the presence of each class is known, was based on orthophotographs for emerged sand, submerged sand and emerged rock classes. The seaweed class was defined according to information collected from divers and fishermen, for the image from 2006, and according to the results from direct observations for the image from 2008. Polygon size ranged from 12 to 168 image pixels. Following these criteria, 30 training polygons were defined for the image from summer 2006, and 42 polygons were established for the image from 2008 (13 and 29 for each fragment) (Table 1).

Table 1. Number of training polygons defined for each image. Due to the size of fragment 1 of the image from 2008, it was not possible to define training polygons for the emerged sand class since it is not represented in the image.

Class	**Image 2006**	**Image 1 2008**	**Image 2 2008**
Submerged sand	9	5	5
Emerged sand	10	0	6
Emerged rock	6	1	5
Seaweed	12	4	11
Total	39	13	29

The three images were subject to angular classification using ENVI 4.6.1 software and the aforementioned training polygons. This method is a physically-based spectral classification that uses an n-D angle to match pixels to reference spectra (Kruse et al., 1993). The algorithm determines the spectral similarity between two spectra (or wavebands values when working with multispectral images) by calculating the angle between the spectra and treating them as vectors in a space with dimensionality equal to the number of bands.

On the other hand, all the images were also subject to a Maximum Likelihood classification. As in the previous cases, for each image this analysis was performed on the original bands as well as the equalized bands, seeking to maximize the spectral differences among classes. In order to assess the obtained results, spectral signatures of each typology were compared. Confusion matrices were used for each image, comparing the values for each pixel obtained by classification with the previously defined training polygons and estimating the degree of accuracy of the classification with respect to the real data.

3. RESULTS

3.1 Visual analysis and interpretation. In the case of the image from summer 2006, histogram equalization allowed for an easy visual distinction of emerged rocky, emerged sandy and submerged sandy areas within the studied depth range (0-10 m). A fourth type of substrate was observed and interpreted as kelp beds (Fig. 4), since its location largely matched the information supplied by divers and fishermen, the submerged rocky areas mapped from orthophotographs, and the bottom maps made by Consellería de Pesca (Catoira et al., 1993). The areas classified as seaweed were mapped, obtaining 37 polygons with a total area of 1684 ha.

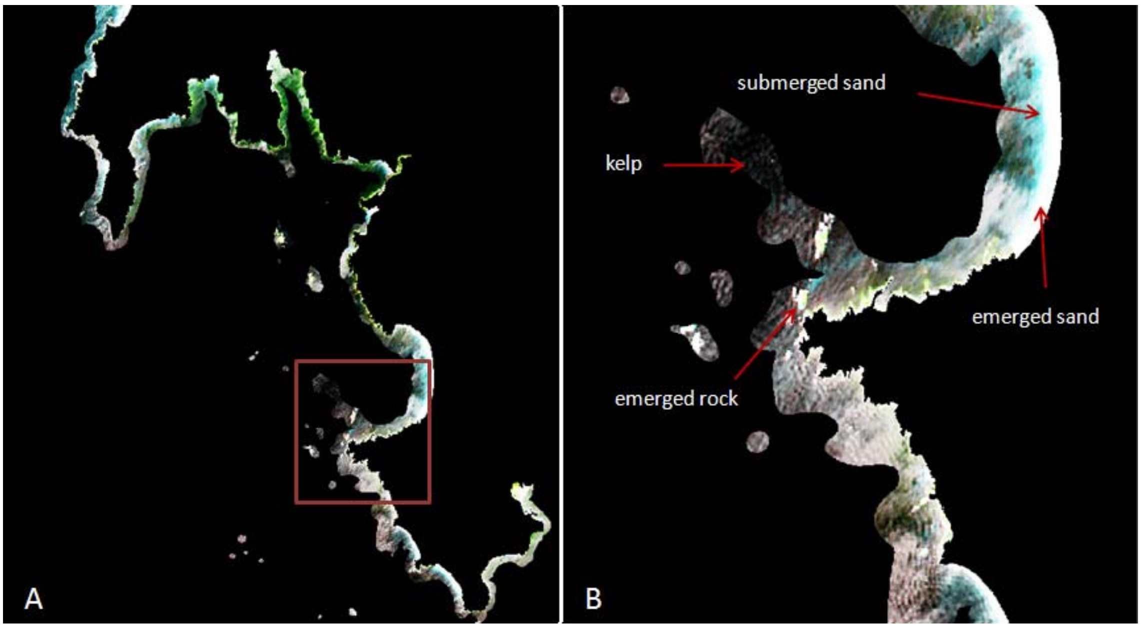

Fig.4. A) Composition of the equalized band, showing emerged rock and sand, submerged sand and seaweed-covered substrate, coincident with the distribution of kelp forests. B) Detail of a zone where the different substrates appears

During the development of this work we have assumed the hypothesis that the submerged rock substrate would be covered by algae because the images utilized were taken in the season of maximum growth rates for the seaweed community. Besides, this hypothesis was supported by fieldwork, for images from 2008 and by the previous experience of the research group in the study zone as well as by information from recreational divers and fishermen. In neither of these cases was observed an area of bare submerged rock that could be mapped by images with a spatial resolution like the ones used in this study. However, if bare submerged rock class was present in a sufficient extension to be mapped with SPOT images, it should be differentiable, because of its high reflectance values.

Analyzing band composition visually, XS3 band showed to be an important waveband for classification of sand substrate (780-890 nm), XS2 band (610-680 nm) is the best one for identifying seaweed-covered areas, and XS1 band (500-590 nm) is the one contributing the least to the classification.

Band equalization in the image from 2008 showed a similar result to the image from 2006, but the effect of wind waves hindered structure definition and therefore also mapping of polygons of kelp beds.

3.1. Band ratio. Any ratio showed clear results in order to map kelp with visual interpretation. *A priori* the most important bands to map kelp would be XS1 (500-590 nm) and XS2 (610-680 nm) because of the infrared absorption of XS3 band (780-890 nm) by the water column, however, neither this band ratio, XS2/XS1, showed coherence with class substrate distribution.

3.2 Cluster analysis. Classes obtained by cluster analysis on images from 2006 and 2008 (both for original and equalized bands) were compared with polygons digitalized by visual interpretation and with the external sources of information used. None of the three classifications obtained (10, 20 and 30 classes) showed correlation with seaweed occurrence.

3.3 Angular classification. Maps of emerged sand and rock resulting from this analysis match the real distribution of both substrates. However, submerged substrates, including forests of Laminariales, do not appear as distinguishable classes.

3.4 Maximum Likelihood Classification. Results obtained by supervised classification (Maximum Likelihood Analysis), both for original and equalized bands, were compared with the classification obtained by visual interpretation and with the external sources of information used. Confusion matrices were generated for each image. The analysis of the original bands showed better results than equalized bands, both for images from 2006 and 2008 (Fig. 5).

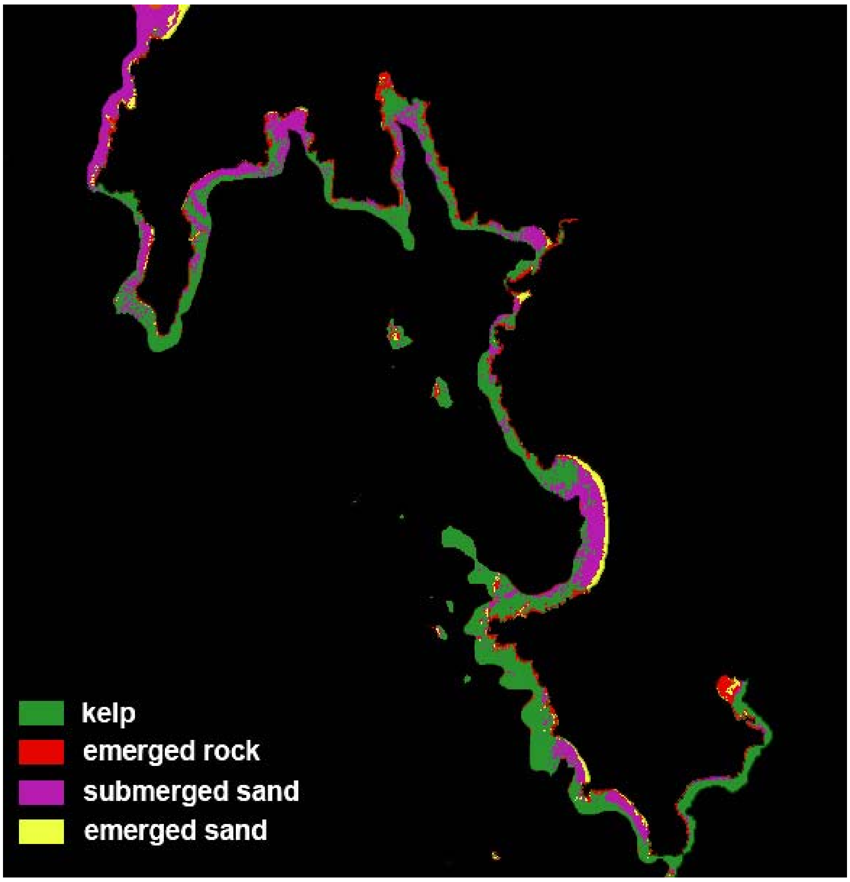

Fig.5. Result of the Maximum Likelihood classification performed on the image from summer 2006 using non-equalized bands. The image shows the four bottom types mapped in this study. The mask used to delimit the study area is represented in black.

The comparison among spectral signatures of each typology, extracted from training polygons, showed an important digital level overlapping (understanding digital level like the numeric value that codes each pixel), for submerged sand and seaweed in all the images, which anticipates difficulties in classification. On the other hand, emerged sand and rock showed significant differences in the three bands, which indicate an effective classification.

As shown in confusion matrices generated from equalized band images (Tables 2 and 3), seaweed polygons were correctly classified in almost 80% of cases for the image from 2006, and in 82.6% and 90% of the cases for the image from 2008. Incorrectly classified polygons were usually assigned to the submerged sand or emerged rock classes, the first due to its similar digital level values to seaweed polygons, and the second due to its high standard deviation values.

Table 2. Confusion matrix for the image from summer 2006. Columns represent classes obtained from training polygons and rows represent the percentage of pixels used to assess the classification in the image. N corresponds to the total number of pixels contrasted for each substrate type.

Class	Seaweed	Emerged sand	Submerged sand	Emerged rock	N
Seaweed	79.59	0	8.84	11.56	147
Emerged sand	0	73.33	11.11	15.56	45
Submerged sand	15.22	0	71.74	13.04	46
Emerged rock	9.78	14.13	1.09	75	7

Table 3. Confusion matrix for the two fragments of the image from summer 2008. Columns represent classes obtained from training polygons and rows represent the percentage of pixels used to assess the classification in the image. N corresponds to the total number of pixels contrasted for each substrate type. The definition of training polygons for emerged sand in fragment 1 of the image was not possible due to its smaller size; therefore the image resulting from supervised classification lacks this type of substrate.

Fragment	Class	Seaweed	Emerged sand	Submerged sand	Emerged rock	N
1	Seaweed	82.61	0	0	17.39	46
	Submerged sand	4.44	0	75.56	20	45
	Emerged rock	44.83	0	0	55.17	29
2	Seaweed	90	0	6.67	3.33	120
	Emerged sand	0	62.5	25	12.5	41
	Submerged sand	22.86	0	60	17.14	35
	Emerged rock	18.4	10.43	17.79	53.37	163

As for the remaining classes, both emerged and submerged sand showed a percentage of accuracy of about 70%, with the lowest results corresponding to fragment 2 of the image from 2008, the most affected by wind waves. The greatest differences among images were found for rock, with over 75% of cases correctly classified for the image from 2006 and over 50% for the two images from 2008.

An overestimation of the seaweed class was observed for the two images from 2008, as shown by the high percentages of sand and rock bottoms that were classified as seaweed (up to 44%).

4. DISCUSSION

Turbidity in Galician waters was expected to be unfavorable for remote sensing studies, although recent studies such as those by Simms & Dubois (2001) and Vahtmäe & Kutser (2007) have been able to distinguish seaweeds in turbid waters.

These limitations arise from the attenuation of the signal from the different substrates by the effect of the water column and suspended matter. In fact, the spectral signatures for the different substrates obtained from the SPOT images showed a high degree of overlapping. Automatic analysis methods, as well as angular classification, have been affected by these conditions, yielding wrong or insufficient classifications. In spite of this, positive results have been obtained with some of the tested methods. It constitutes an advance regarding the study made by Catoira et al. (1993) where no correlation was observed between information from Landsat 5TM satellite images and field mapping.

Visual interpretation allowed the correct mapping of sea bottoms up to 10 m depth, yielding similar results to those obtained by Simms & Dubois (2001), who were able to detect the presence of *Laminaria longicruris* between 0 and 6 m depth through the use of the SPOT-HRV sensor in the Canadian Atlantic coast and XS2 band (610-680 nm) has been shown to be the most useful for defining kelp forests. This result agrees with other studies stating that the predominant reflectance characteristic of the Order Laminariales is the occurrence of two maximums in 600 and 650 nm (Karpouzli et al., 2004).

In the case of the maximum likelihood classification, the classification percentages obtained were high (over 70 %) for all substrates. Moreover, direct observations done in 2008 corroborated the results obtained in the classification done on the image from 2006, since the presence of kelp beds was observed in all the areas classified as such.

However, although the substrate distribution obtained by these classifications agree with the external sources of information used (orthophotographs and direct observations), no rocky bottoms without seaweed coverage could be defined. The orthophotographs do not allow for their differentiation and field observations have not found this type of substrate, making it impossible to establish training polygons for this class.

Another aspect worth noting in the evaluation of our results are the data obtained by Maritorena et al. (1994) and Andréfouët et al. (2001) supporting maximum reflectance values of 600 and 650 nm for brown seaweeds *Sargassum* and *Trubinaria*, which would imply that multispectral images such as those analyzed here could not allow for the differentiation among species of Laminariales and areas covered with *Sargassum* and *Cystoseira*, both relatively abundant and covering large areas in the Galician coast (Fernández et al., 1990; Bárbara & Cremades, 1993; Pérez-Ruzafa et al. 2003).

As noted in the introduction, the present study constitutes an approach to the mapping of large seaweed forests and other types of substrates in coastal waters. Therefore, these results could be improved by the use of images with a higher spectral, spatial and radiometric resolution; performing new field calibrations simultaneously to the acquisition of images. This issue would yield intensive information of the study area in order to accurately compare remote sensing with real data; eliminating the effect of the water column; and establishing a greater number of training polygons. Thus solving the difficulties in differentiating among seaweed species and in detecting submerged bare rock.

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CHAPTER III

CHAPTER III

MAPPING BENTHIC MACROALGAL COMMUNITIES IN THE COASTAL ZONE USING CHRIS-PROBA MODE 2 IMAGES

ABSTRACT

Ecological importance of benthic macroalgal communities in coastal ecosystems has been recognised all over the world. The application of remote sensing to study these communities presents certain advantages respect to *in situ* methods. In the present study three CHRIS-Proba images were used to analyse macroalgal distribution in the Seno de Corcubión (NW Spain). The use of this sensor represent a challenge given that its design, build, and deployment program is intended to follow the principles of the "faster, better, cheaper". To assess the application of this sensor to macroalgal mapping, two types of classifications were carried out: Maximum Likelihood and Spectral Angle Mapper (SAM). Maximum Likelihood classifier showed positive results, reaching overall accuracy percentages higher than 90% and kappa coefficients higher than 0.80 for the bottom classes *shallow submerged sand*, *deep submerged sand*, *macroalgae less than 5 m* and *macroalgae between 5 and 10 m depth*. The differentiation among macroalgal groups using SAM classifications showed positive results for green seaweeds, however, the differentiation between brown and red algae was not clear in the study area.

Keywords: remote sensing, benthic mapping, macroalgae, CHRIS, hyperspectral, coastal zone

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1. INTRODUCTION

Benthic algal communities play an important role in coastal ecosystems due to their ecological functions. These communities are essential for many organisms as habitat (Birkett et al, 1998, Pallas *et al.*, 2006, Cacabelos *et al.*,2010), mating and nursery grounds (Borg *et al.*, 1997 and Shaffer, 2003) feeding areas (Velando and Freire, 1999; Lorentsen *et al.*, 2004) and refuge (Bushmann, 1990; Gotceitas *et al.*, 1997). Another relevant aspect is their important contribution to primary production (Mohammed and Fredriksen, 2004), the sediment stabilization and coastline protection (Madsen *et al.*, 2001), besides being a suitable indicator on the ecological status of coastal communities (Juanes *et al.*, 2008).

The use of remote sensing in monitoring these communities presents certain advantages: the method is non invasive, allows to study large areas as well as mapping inaccessible zones and provides the possibility of repetitive cover of a target area. Besides, this method is faster and less costly than conventional field methods. Due to its advantages remote sensing has been applied in many locations around the world to map macroalgal communities in many environmental conditions: Kutser *et al.* (2003, 2006a) and Karpouzli *et al.*, (2004) mapped seaweeds associated to coral reefs, Pe'eri *et al.* (2008) mapped algae and eelgrass in a estuary, Dekker *et al.* (2005) seagrasses in a lake, Alberotanza *et al.* (1999) submerged vegetation in lagoons, Vahtmäe *et al.* (2006) and Kutser *et al,* (2006b) macroalgae in turbid coastal waters and Henning *et al.* (2007) in rocky intertidal zones. However, in spite of the results obtained with these techniques only two references were found about remote sensing use to map macroalgal communities in our study area (Catoira *et al.*, 1993, Casal *et al.*, 2011).

Remote sensing sensors can be divided into two groups based on their spectral resolution: multispectral and hyperspectral and both types of sensors have been used in mapping benthic algal cover. Multispectral systems commonly collect data in three to six spectral bands in a single observation from the visible and near-infrared regions of the electromagnetic radiation spectrum (Govender *et al.*, 2007). On the other hand, hyperspectral sensors acquire imagery in a high number of contiguous and narrow spectral bands producing much more detailed spectral data. In spite of these advantages, some limitations exist in the hyperspectral technologies. Spatial resolution of satellite sensors like Hyperion (30 m) is too coarse in many circumstances and hyperspectral airborne imagery produces large data volume involving a high data-processing effort and cost compared to satellites (Govender *et al.*, 2007).

The first satellite of the PROBA series was launched in October 2001. The Project for On Board Autonomy (PROBA) satellite is the first European Space Agency's (ESA) small satellite built for small scientific missions (Jorgensen *et al.*, 2005), and is classified as micro-satellite with a mass of 94 kg and size of 80x60x60 cm. Its design, build, and deployment program is intended to follow the principles of the "faster, better, cheaper". This satellite was introduced by NASA to provide more cost effective space missions (Barnsley *et al.*, 2004). Its orbit is elliptical and at the launch the altitude varied between 550 km and 670 km. Both the semi-major axis and the equator crossing time have shown minimal variation since launch offering relatively stable conditions for Earth observations (Cutter *et al.*, 2007).

The main instrument on board of PROBA-1 platform is the Compact High Resolution Imaging Spectrometer (CHRIS). CHRIS is a "push-broom" imaging spectrometer designed by SIRA Electro-Optics Ltd. (U.K.) to collect data for land and sea investigation as well as aerosol measurement providing hyperspectral and multiangular images. CHRIS sensor combines the advantages of satellite platforms (homogeneous quality, long-term data suitable for highly automated processing) with a relatively high spatial and spectral resolution intermediate between ocean colour satellite sensors and hyperspectral airborne sensors (Van Mol and Ruddick, 2004).

CHRIS acquires a set of five images of the same scene at a Fly-by Zenith Angle (FZA) of +55º, +36º, 0º, -36º and -55º during the same sun-synchronous polar orbit. Each image set has an associated "fly-by position" on the ground (roughly the image centre) that corresponds to the Minimum Zenith Angle (MZA), defined as the off-nadir inclination of the sensor viewing direction in the plane perpendicular to the satellite orbit (Barducci *et al.*, 2007). Images present 18, 37 or 63 spectral bands with 12 bit digital signal between 405 and 1050 nm and a spatial resolution of 17 m or 34 m depending on the mode.

The unique characteristics of CHRIS-Proba, being the only multiangular hyperspectral sensor at present, have favoured a growing community of CHRIS data users in its years of service. However the inherent difficulty to process this complex data to Level 2 (georeferenced surface reflectance) hinders the production of scientific results (Alonso *et al.*, 2009).

Up to now CHRIS has been used in several studies applied to water environments both in inland and coastal zones. For example, mapping coral reefs (Sterckx *et al.*, 2005; Miller and Merton, 2006), water quality in coastal areas (Lavander *et al.*, 2004), wetland monitoring (Barducci *et al.*, 2007) and water quality in inland water (Ruiz-Verdú *et al.*, 2005). However, no reference was found about mapping macroalgal communities. In this context the aim of this study is to assess the use of CHRIS images to map macroalgal communities and other benthic substrates in the coastal zone, as well as assessing the differentiation among macroalgal groups (green, brown and red).

2. MATERIAL AND METHODS

2.1 Study area

The study area was located in the Seno de Corcubión (NW Galicia, Spain) (Fig.1) that represents an open bay south-oriented with semi-diurnal tides, presenting an approximate range of 2-4 m. The study was carried out in the coastal zone defined by the CHRIS-Proba image cover and the 10 m bathymetric line. The depth limit was established taking into account results reached in other similar works (Simms and Dubois, 2001; Vahtmäe *et al.*, 2006).

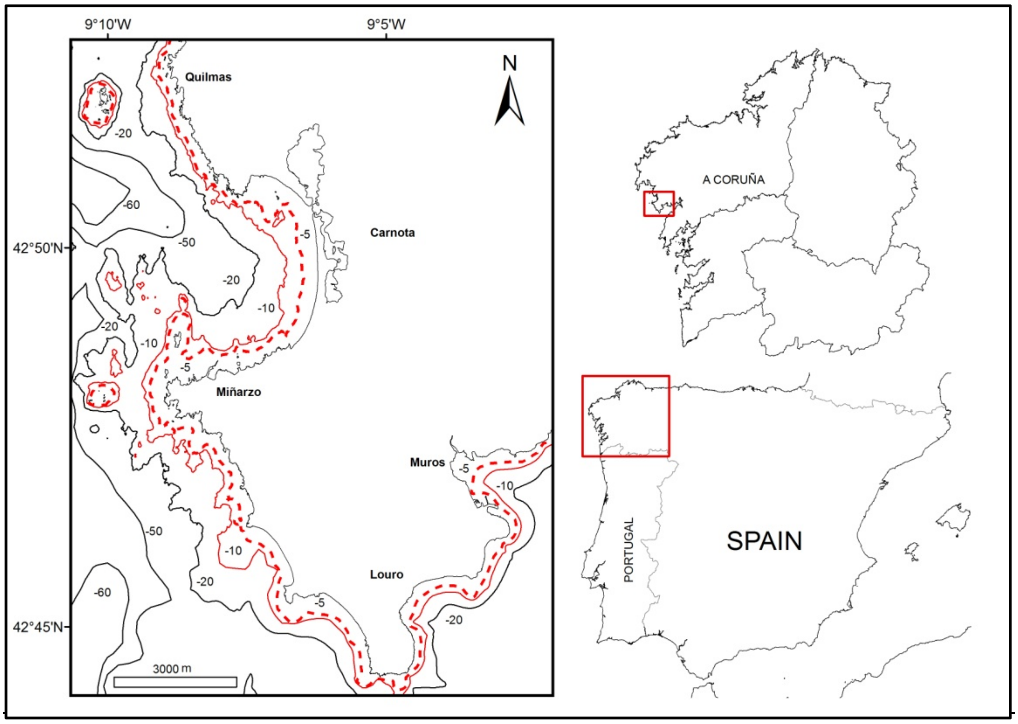

Fig. 1. The study zone was located in the Seno de Corcubión (NW Spain). The bathymetric 10 m line is represented with a solid red line and the 5 m bathymetric line is represented with a red dotted line.

The study site is a semi-exposed zone mostly covered with rocky substrate suitable for development of a great variety of benthic algae communities. The upper intertidal zone is dominated by brown macroalgae like *Fucus vesiculosus,* red macroalgae like *Chodrus crispus* and *Mastocarpus stellatus* and in lesser extent green macroalgae (*Ulva sp*.). On the other hand the high subtidal zone is dominated by large brown macroalgae like *Laminaria ochroleuca*, *Sacchroriza polyschides*, *Cystoseira baccata*, *Halidrys siliquosa* and the invasive *Sargassum muticum.* Red algae, like *Asparagopsis armata,* is also present in this zone while the presence of green algae is nearly nonexistent. Characteristics macroalgal belts in the intertidal zone are quite homogenous while in the high subtidal zone these communities are more heterogeneous being usual to observe mixed assemblages of red and large brown seaweeds. The development of these communities depends on the season reaching their highest biomass in spring-summer.

2.2 CHRIS images

A dataset of three cloud-free images were taken over the study zone (Table 1). These images were acquired in Mode 2, optimised for water studies covering an area of 13 x 13 km at nadir (748 x 748 pixels). This mode presents a ground spatial resolution of 17 m and 18 spectral bands between 411 and 1019 nm with a spectral width between 6 and 33 nm. All images were acquired through the "*ESA Category-1 scheme*" program.

Table 1. Image acquisition details. Start and Stop hour show the image acquisition time, Low tide indicates the time of the lowest tide for this data and Tide height shows the height of the tide at the image acquisition time.

Data	Start Hour (UTC)	Stop Hour (UTC)	Low tide (UTC)	Tide height (m)
23/09/2008	11:09	11:13	9:42	2,8
02/12/2008	10:53	10:57	11:27	1,22
11/07/2009	11:01	11:05	10:57	0,72

In spite of CHRIS sensor provides images in different angles, in this study only nadir images were analysed. For this choice was taken into account the results obtained in a preliminary analysis and the sensitivity that some view angles show to swell conditions and sun glint.

2.3 Field survey

Three field campaigns were carried out close to each image acquisition date. The field work consisted of 100 m length transects (Table 2) carried out by divers. During the transects data about the relative abundance of green, brown and red macroalgae and substrate type after each meter were collected (Fig.2). Relative abundance was visually registered along these transects, codified according to a scale from 0 to 4 (absent, present, low-abundant, abundant or highly abundant). Presence / absence of each type of substrate was used to establish training and validating areas in parametric and non-parametric classifications.

Table 2. Date of field work and number of transects carried out in the study zone for each image acquisition.

Image date	Field work date	Number of transects
23/09/2008	May, August 2008	19
02/12/2008	November 2008	18
11/07/2009	May, July 2009	19

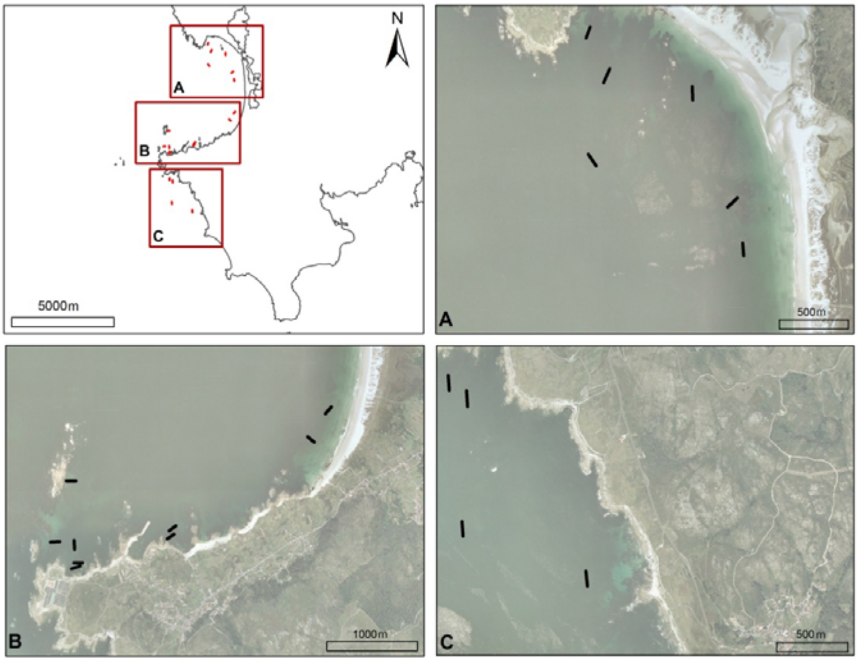

Fig. 2. Location of diving transects. Each transect was 100 m long and each meter relative abundance of the different green, brown and red macroalgal species and substrate type were reported.

2.4 Data analysis

2.4.1. Pre-processing

Before the image classification a pre-processing was carried out consisting of several steps: 1) Noise reduction, 2) Atmospheric correction, 3) Geometric correction and 4) Masking.

2.4.1.1 Noise reduction

Hyperspectral images acquired by push-broom sensors such as CHRIS can be affected by two kinds of noise: drop-out and striping. The drop-out is due to that the transmission of CHRIS channel 2 (odd and even pixels from each CCD row are read in parallel) randomly fails producing anomalous values at the odd pixels in some image rows. Striping is a multiplicative noise in image columns that comes from irregularities of the entrance slit of the spectrometer and CCD elements in the across-track direction. Drop-out and striping noise cause, respectively, horizontal and vertical distortions in the image affecting to the subsequent treatment. Both kinds of noise were corrected using the algorithm developed by Gómez-Chova *et al.* (2008) and implemented in the BEAM VISAT 4.6.1 software (Brockmann Consult) provided by ESA.

2.4.1.2 Atmospheric correction

In the visible to near-infrared spectral range covered by CHRIS, aerosols and water vapour are the most important atmospheric distortion sources. Aerosol contribution takes place as a continuum in spectral terms, with the largest distortion in the shortest visible wavelengths (Alonso *et al.*, 2009). Water vapour absorptions must be considered in those modes where water vapour absorptions are registered, whereas the aerosol influence must be taken into account in all the operations modes (Alonso *et al.*, 2009). In the most general case, defined by modes 1 and 5, the entire atmospheric correction processing consist of characterization of spectral calibration, Aerosol Optical Thickness (AOT) retrieval, Column Water Vapour (CWV) retrieval, reflectance retrieval and data recalibration. Calibration assessment and CWV retrieval are not performed over modes 2, 3 and 4 due to the insufficient sampling of atmospheric absorption features (Alonso *et al.*, 2009).

The retrieval of atmospheric constituents and surface reflectance involves modelling the radiative transfer across the atmosphere. A simple but accurate formulation of the TOA signal in terms of surface reflectance and atmospheric optical parameters is necessary (Alonso *et al.*, 2009). Since no knowledge of the surface bidirectional reflectance distribution factor (BRDF) is available prior to the atmospheric correction, the usual Lambertian approach (Nicodemus *et al.*, 1997) for the surface reflectance is assumed.

The MODerate resolution TRANSmittance (MODTRAN4) atmospheric radiative transfer code (Berk *et al.*, 2003) was used for the generation of a Look-Up Table (LUT) that provides the atmospheric parameters from multidimensional linear interpolation (Alonso *et al.*, 2009). This algorithm is implemented in the BEAM VISAT software allowing automate the processing. The necessary inputs for this procedure are read from the metadata attached to the original images. MODTRAN4 has been selected for its good parameterisation of both scattering and absorption of light in atmosphere (Guanter *et al.*, 2005a, 2005b). The LUT depends on 6 free input parameters: view zenith angle, solar zenith angle, relative azimuth angle, surface elevation, aerosol optical thickness at 550 nm (AOT550) and CWV (Guanter *et al.*, 2005a, 2005b). The atmospheric vertical profile is given by the default midlatitude summer atmosphere, the aerosol type is fixed to the continental model, and the ozone concentration is fixed to 7.08 $g \cdot m^{-2}$. The LUT was generated using the *New Kurucz* extraterrestrial solar irradiance data base in MODTRAN4 (Guanter *et al.*, 2005a, 2005b). AOT can also be defined by the user if some a priori information from external data is available; however this was not the case of this study.

This atmospheric correction module must follows the noise reduction and cloud screening in a complete CHRIS/PROBA processing chain, even though cloud screening could be skipped when no cloud is observed (Alonso *et al.*, 2009). The algorithm used in this correction was developed by Guanter *et al.* (2005) and implemented in BEAM VISAT software. Outputs of the procedure were reflectance images.

After atmospheric correction some strange values were observed in certain wavelengths. This issue was reported for some authors as Ruíz-Verdú *et al.* (2005) for the first two bands in inland water and by Alonso *et al.* (2009) who reported the difficulty to process CHRIS data to Level 2. Taking this into account and the strong absorption of light by water column in red and near-infrared wavelength, only bands in spectral range between 490 and 781 nm were analysed. In this range bands W4 (510 nm), W6 (561 nm), W8 (590 nm), W11 (672 nm) and W13 (686 nm) were also eliminated from the analysis because these bands presented anomalous high values (Table 3).

Table 3. Spectral description of CHRIS Proba mode 2 bands. The table shows the maximum, minimum and medium wavelengths of each band as well as their band width. The table also shows the bands used in this study.

Band	Min (nm)	Max (nm)	Mid (nm)	Width (nm)	Bands used
W1	406	415	411	10	
W2	438	447	442	9	
W3	486	495	490	9	W3
W4	505	515	510	10	
W5	526	534	530	9	W5
W6	556	566	561	10	
W7	566	577	570	8	W7
W8	585	596	590	12	
W9	618	627	622	9	W9
W10	646	656	651	10	W10
W11	666	677	672	11	
W12	677	683	680	6	W12
W13	683	689	686	6	
W14	700	712	706	12	W14
W15	752	759	755	7	W15
W16	773	788	781	15	W16
W17	863	881	872	18	W17
W18	1003	1036	1019	33	

2.4.1.3 Geometric correction

Images were corrected with ENVI 4.6 software using ortophotos corresponding to the study area. These ortophotos, provided by the *Fondo Galego de Garantía Agraria* (FOGGA) dependent of the *Consellería de Medio Rural* of Autonomous Galician Government, were resampled from 0.5 m of pixel size to 15 m to facilitate the association between CHRIS image and orthophotos. To georreference the images 50 ground points were taken trying to choose invariable structures obtaining a RMS less than 0.5 pixels.

2.4.1.4 Masking

To eliminate the spectral variability caused by land and marine areas outside the study area, a terrestrial and a bathymetric mask were applied to the images.

An increase of sun glint effect was observed when mask was applied. This effect consists of a specular reflection of light from water surfaces that constitutes a serious confounding factor for remote sensing of water column properties and benthos (Kay *et al.*, 2009). Due to strong absorption of radiation by water molecules in the near infrared part of electromagnetic spectrum (NIR), this part could give an indication of the amount of glint present at the image as zero water leaving signal can be assumed. Following this assumption NIR values were subtracted from visible bands using the index VIR-NIR. After applying this index, images improved considerably their visual interpretation (Fig.3).

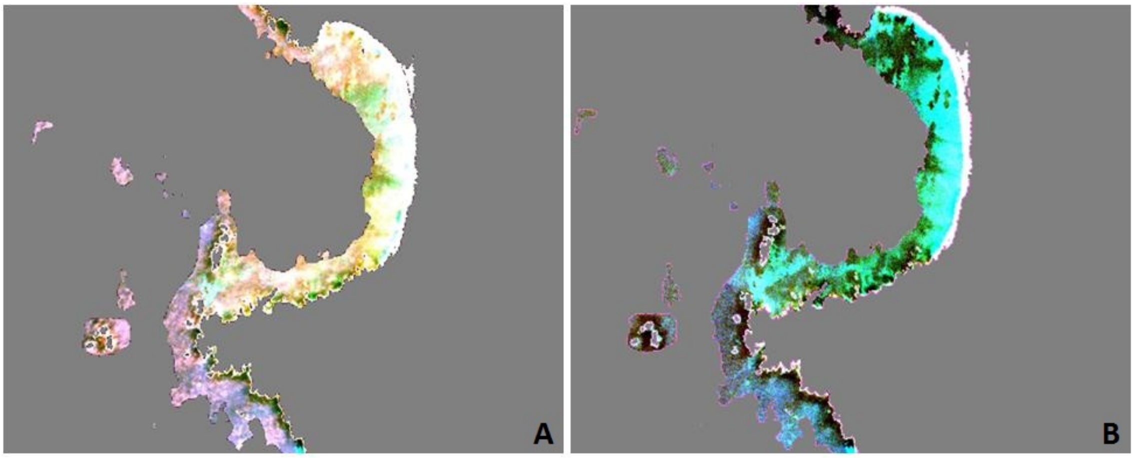

Fig. 3. Image detail corresponding to 23/08/2009 date. A) Image before sunglint correction. B) Image after sunglint correction

2.4.2 Assessment of macroalgae classification and other benthic substrates

The first step to assess CHRIS images efficiency in mapping macroalgae and other benthic substrates was the establishment of training areas that were defined with visual interpretation and field observations. Minimum size of these areas were established following Schowengerdt (1997) who declares that is necessary to select a minimum of m+1 pixels per category, being m the number of bands used in the analysis, in our case 11 pixels (10+1). Thus, training areas for the classes: *shallow submerged sand*, *deep submerged sand*, *macroalgae less than 5 m* and *macroalgae between 5 and 10 m depth* were established. Sand categories were defined through visual interpretation and the differentiation of the two classes of macroalgae was established using the 5 m bathymetric line.

The n-D visualizer was used in ENVI sofware to select the most representative pixels of each class. Before supervised classification, the spectral separability among each pair of endmember classes was studied for each image. In the three images all pairs showed values higher than 1.9 indicating a good separability among them (Richards, 1999). These endmembers were used as training areas in the supervised image classification, which was performed using the parametric decision rules Maximum Likelihood, Minimum distance and Mahalanobis distance. To validate classification results independent ground-truth areas were used which were not included in the training of the supervised classification. These areas, as the training areas, were established using visual interpretation and field observations (Table 4) and subjected to the same processing.

Table 4. Detail of training and validating areas. This table collects the number of pixels and their cover in m^2 for each class used in supervised classifications.

		Shallow sand		Deep sand		Macrolgae less 5 m		Macroalgae between 5 and 10 m	
Data	Type	nº pixel	m^2	nº pixel	m^2	nº pixel	m^2	nº pixel	m^2
	training	142	41.04	203	58.67	29	8.38	75	21.67
23/09/2008	validating	88	25.43	135	39.01	42	12.14	31	8.96
	training	49	14.16	111	32.08	119	34.39	63	18.21
02/12/2008	validating	56	16.18	58	16.76	71	20.52	51	14.74
	training	139	40.17	99	28.61	117	33.81	154	44.50
11/07/2009	validating	140	40.46	106	30.63	95	27.45	113	32.66

For the assessment of classification accuracy, a confusion matrix (error matrix) was prepared, comparing the classification results on a category-by-category basis. An error matrix is a square array of numbers set out in rows and columns which express the number of sample units, in our case pixels, assigned to a particular category comparing results and validating areas (Congalton, 1991). The kappa coefficient was also calculated to compare the accuracy of different classifiers. This coefficient is an indicator of overall agreement of a matrix. It measures the proportion of agreement after chance agreement has been removed from consideration (Cohen, 1960). In this work to assess kappa coefficient the scale established by Landis and Koch (1997) was followed. These authors establish that: kappa ≤ 0 shows total disagreement, between 0.01 and 0.20 light agreement, between 0.41 and 0.60 moderate, between 0.61 and 0.80 high and between 0.81 and 1.00 total or nearly total agreement among diagnostics. Besides these indicators, the overall accuracy and commission and omission errors were analysed. Overall accuracy is computed by dividing the total correct (i.e. the sum of the major diagonal) by total number of pixels in the error matrix (Congalton, 1991) while commission and omission errors correspond with errors of inclusion and exclusion in the classified classes.

2.4.3 Assessment of the differentiation among macroalgal groups (green, brown and red)

Before image classifications, typical spectra of green, brown and red macroalgae measured in the field were analyzed. The spectra were resampled to CHRIS wavelengths and analyzed by continuum removal. Continuum removal is a normalisation technique, resulting in a curve with values from 0 to 1, which emphasises the location and depth of individual absorption features (Clark and Roush, 1984) letting a comparison from a common baseline.

This analysis (Fig.4) shows spectral differences between green macroalgae and brown and red macroalgae but differences between brown and red macroalgae are not clear. This agrees with the results of Kutser *et al.*, (2006c) that fine spectral resolution (10 nm or better) in the wavelength range between 500 and 650 nm is needed to be able to separate green and brown macroalgae based on their spectral signatures.

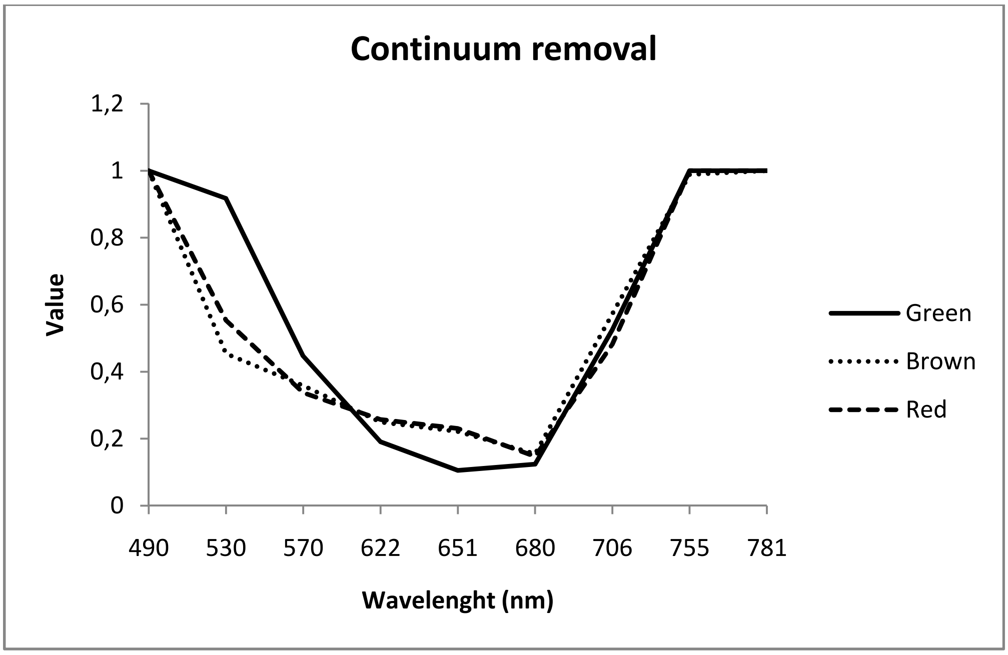

Fig. 4. Continuum removal spectra of green, brown and red macroalgae. The biggest differences among the spectra are located at 530, 561, 570, 622, 651, 672 nm that correspond with W5, W6, W7, W9, W10 and W11 bands respectively.

The biggest differences among the spectra, using continuum removal analysis, are located at 530, 561, 570, 590, 622, 651, 672 nm that correspond with W5, W6, W7, W8, W9, W10 and W11 bands respectively. However, only W5, W7, W9 and W10 bands were classified using Spectral Angle Mapper (SAM) due to W6, W8 and W11 present anomalous values after atmospheric correction. SAM algorithm determines the similarity between two spectra by calculating the spectral similarity between them, expressed in α-values (Kruse *et al.*, 1993). The α-value represents the angle difference between two spectral endmembers. The spectra are treated as vectors in a space with dimensionality equal to the number of spectral bands used (Kruse *et al.*, 1993). This technique is relatively insensitive to illumination and albedo effects because the angle between two vectors is invariant with respect to the length of the vectors (Kruse *et al.*, 1993). Different angles between 0.10 and 0.4 radians were tested following Kruse *et al.* (1993) Dekker *et al.*, (2003) and Kutser *et al.*, (2006a).

Before SAM classifications a mask that eliminates all substrates except algae was applied. This mask was made using the Maximum Likelihood results described above. Another mask was also applied to eliminate waters more than 10 m deep. SAM classifications were applied including green, brown and red macroalgae endmembers and repeated excluding these last ones from the analysis.

3. RESULTS

3.1 Assessment of macroalgae classification and other benthic substrates

Classification of macroalgae using CHRIS mode 2 images shows positive results. Regarding overall accuracy, confusion matrix and kappa coefficient, the classifier that shows the best results in all analysed images was Maximum Likelihood. The overall accuracy exceeds 90% in all cases and kappa coefficient is also high indicating high or nearly total agreement according to Landis and Koch (1997) scale (Table 5).

Table 5. Overall accuracy and kappa coefficient obtained with Maximum Likelihood classifier.

Image Date	Overall accuracy (%)	Kappa
23/09/2008	94.59 (280/296)	0.92
02/12/2008	90.25 (213/236)	0.87
11/07/2009	98.68 (448/454)	0.98

Analysing classification percentages of different classes in the confusion matrix (Table 6), it could be observed that all benthic types have percentages higher than 74 %. The best-classified class is *shallow submerged sand*, reaching in all images 100% due to its high reflectance values.

Table 6. Confusion matrix of all Maximum Likelihood classifications carried out. The columns represent the reference data while the rows indicate the classification generated from the remotely sensed data. All data are represented in percentages.

23/09/2008	**Shallow submerged sand**	**Deep submerged sand**	**Macroalgae less than 5 m**	**Macroalgae between 5 and 10 m**
Unclassified	0	0	0	0
Shallow submerged sand	**100**	5.19	0	0
Deep submerged sand	0	**94.81**	16.67	0
Macroalgae less than 5 m	0	0	**80.95**	3.23
Macroalgae between 5 and 10 m	0	0	2.38	**96.77**
02/12/2008	**Shallow submerged sand**	**Deep submerged sand**	**Macroalgae less than 5 m**	**Macroalgae between 5 and 10 m**
Unclassified	0	0	0	0
Shallow submerged sand	**100**	0	0	0
Deep submerged sand	0	**100**	25.35	9.8
Macroalgae less than 5 m	0	0	**74.65**	0
Macroalgae between 5 and 10 m	0	0	0	**90.2**
11/07/2009	**Shallow submerged sand**	**Deep submerged sand**	**Macroalgae less than 5 m**	**Macroalgae between 5 an 10 m**
Unclassified	0	0	0	0
Shallow submerged sand	**100**	0.94	0	0
Deep submerged sand	0	**98.11**	4.21	0
Macroalgae less than5 m	0	0.94	**95.79**	0
Macroalgae between 5 and 10 m	0	0	0	**100**

On the other hand, *deep submerged sand* shows high percentages too, reaching values higher than 94% in all cases. Regarding algae classes, *macroalgae less than 5 m* shows percentages higher than 80%, with the exception of 02/12/2008 image that shows a percentage around 74% for this class. Both substrates have low reflectance values and their differentiation is difficult using visual interpretation. This is reflected in the relatively high commission and omission errors obtained (Table 7). The confusion matrix shows this same result indicating a little confusion between this class and *deep submerged sand*. *Macroalgae between 5 and 10 m* class shows elevated classification accuracy percentages, higher than 90% in the three images, and commission and omission errors lower than 9%, indicating a good classification and little confusion with other classes.

Table 7. Commission and omission errors (in percentages) for each class.

		Shallow submerged sand	**Deep submerged sand**	**Macroalgae less than 5 m**	**Macroalgae between 5 and 10 m**
23/09/2008	Commission	7.37	5.19	2.86	3.23
	Omission	0	5.19	19.05	3.23
02/12/2008	Commission	0	28.40	0	0
	Omission	0	0	25.35	9.80
07/11/2007	Commission	0.71	3.70	1.09	0
	Omission	0	1.89	4.21	0

Assessing visually the Maximum Likelihood results (Fig. 5) all images show a coherent classes distribution that agree with confusion matrix results. A decrease of macroalgal cover is observed in winter (02/12/2008) as it was seen in the comparison of this image with the images taken in summer (23/09/2008 and 11/07/2009). This result is supported comparing a common zone around 10 km^2 in the three images where a macroalgal cover of 4.98 km^2 was observed for 11/07/2009 image, 4.37 km^2 for 23/09/2008 and 3.59 km^2 for 02/12/2008.

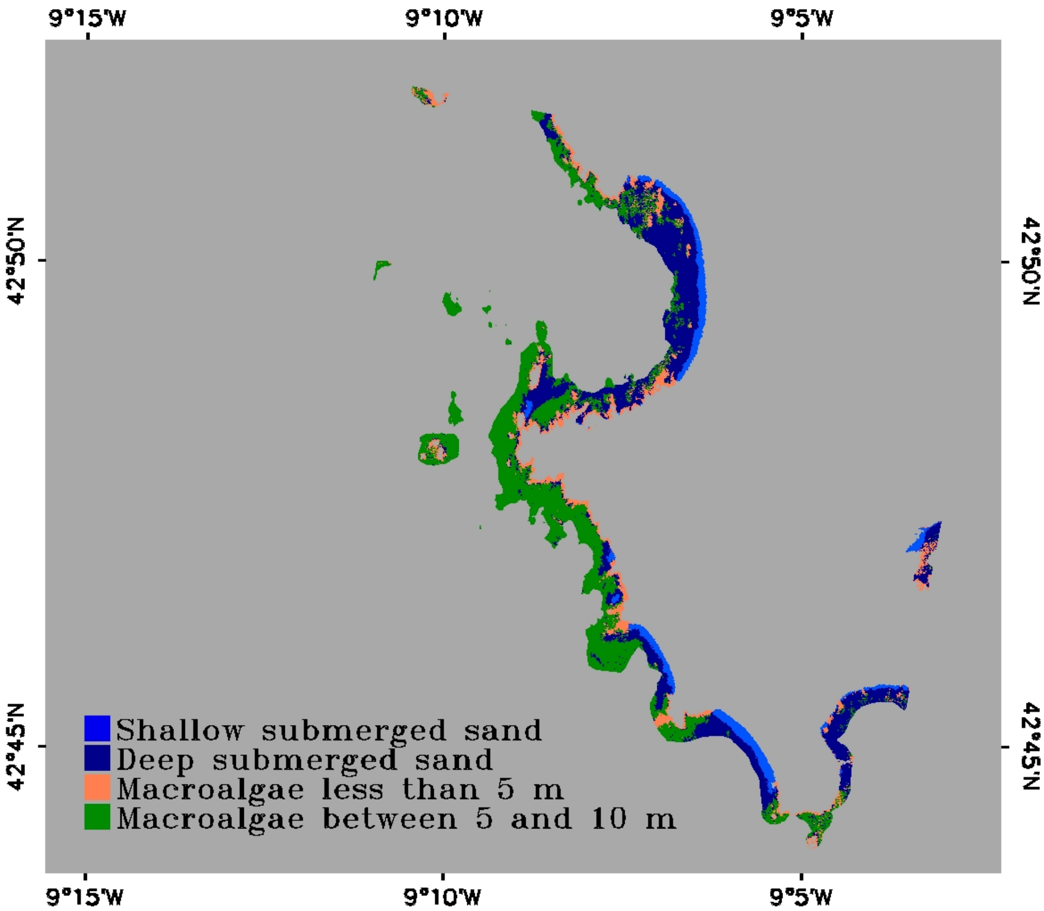

Fig. 5. Maximum Likelihood classification results using 11/07/2009 image. The image shows the four bottom types mapped with Maximum Likelihood classifier. The mask used to delimit the study area is represented in grey.

3.2 Assessment of the differentiation among macroalgal groups (green, brown and red)

Continuum removal analysis shows that CHRIS sensor allows the spectral differentiation of green from brown and red macroalgae but is not sufficient to separate red from brown ones. This result is based on spectral signatures of seaweeds even if they are not covered with water. A few meters of water covering macroalgae produces a decrease in bottom signal received by satellite sensor making this differentiation more difficult or even impossible in some cases, still using high spectral resolution hyperespectral instruments (Vahtmäe *et al.* 2006).

In our case SAM classifications were applied to assess CHRIS sensor ability to difference green, brown and red macroalgae. After some tests with SAM classifications it was observed that 0.2 radians gave the optimal results. In other cases either parts of the image remained unclassified or the classification results did not change (using higher values) obtaining the same result as Kutser *et al.*, (2006a).

When the red macroalgae endmembers were also used, water column effects on the classification results were observed. This effect made that deeper algae were classified as red algae while shallow algae were classified as brown algae confirming the good separability between *macroalgae lower 5 m* and *macroalgae between 5 and 10 m* endemembers (1.9) observed in Maximum Likelihood classifications (Fig.6). Comparing SAM results with field observations, zones classified as red correspond in field with brown algae or zones where brown and red algae are mixed. If red macroalgae endmembers are not added to the classification, pixels classified as red are classified as brown macroalgae. In both classifications some isolated pixels are classified as green algae however, the absence of field observations in these pixels does not allow validating these results.

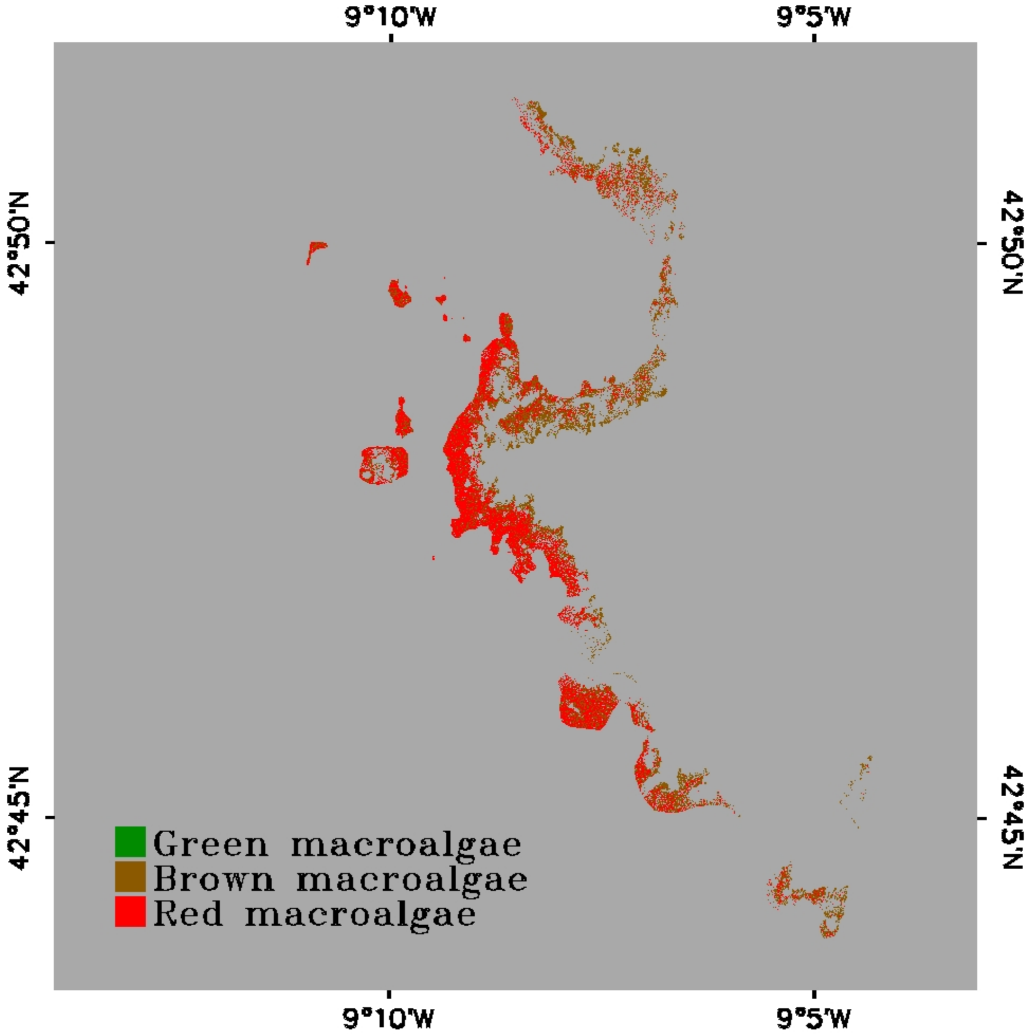

Fig. 6. SAM classification results using 23/09/2008 image. This figure shows the water column effect producing the classification of deep macroalgae as red macroalgae while shallow macroalgae were classified as brown macroalgae. Green macroalgae class occurs only as some isolated pixels. Brown and red macroalgae are not theoretically differentiable using CHRIS sensor as it was showed by continuum removal analysis.

4. DISCUSSION

The use of CHRIS images presents certain advantages in mapping coastal zones in comparison with traditional ocean colour sensors like SeaWIFS, MODIS or MERIS and with multispectral sensors such as IKONOS, Landsat, Quickbird or SPOT. Traditional ocean colour sensors have been used successfully for water quality monitoring (e.g. Chen *et al.*, 2007), to study cyanobacterial blooms (e.g. Reinart and Kutser, 2006), to assess the variability of microphythobentos in the intertidal areas (Vanhellemont, 2009) or for benthic mapping (Kutser *et al.*, 2006c). However, ocean colour sensors have coarse spatial resolution (~1000 m to 250 m) compared to the extent of macroalgal belts (in meters to tens of meters). On the other hand, multispectral sensors as Landsat or SPOT have better spatial resolution (20-30 m) which is sometimes comparable to the scale of benthic habitat units. However, these sensors are not designed for aquatic environments and they lack the sensitivity to discriminate spectra because the number of bands is low and not all of them can penetrate into the water. Bands in the visible part of the spectrum can penetrate water column; nevertheless, the width of the spectral bands and their location are not adequate to discriminate between different macroalgae groups (Kutser *et al.*, 2006b). Thus, these sensors are suitable for benthic mapping in quite homogeneous zones and preferably in clear waters (Simms and Dubois, 2001; Pascualini *et al.*, 2005; Torrusio, 2009).

Benthic coastal environments are spectrally and spatially complex involving the need for high spectral and spatial resolution to achieve high classification accuracy. Airborne sensors provide high spatial and spectral resolution and have been used to create quite accurate benthic thematic maps (Bertels *et al.*, 2008; Pe´eri *et al.*, 2009; Hunter *et al.*, 2010) but their cover is reduced and their economic high cost. CHRIS appears as an intermediate sensor providing a higher and more repetitive cover than airborne and a higher spatial resolution than traditional ocean colour satellites.

CHRIS Proba also offers a specific capacity for multiangular measurements, that has been used effectively in terrestrial studies (Begiebing and Bach, 2004; Sykioti *et al.*, 2011) being especially effective in terrains with different slopes. Multiangular images were also used for water quality studies (Van Mol and Ruddik, 2004; Ruíz-Verdú *et al.*, 2005) where parameters of the water surface where studied. However, the multiangular capacity of CHRIS Proba is not an advantage in the case of benthic habitat mapping. Under other angles than the nadir light has to penetrate longer distances in water column. Water and its constituents absorb and scatter light strongly and have a strong impact on the spectral signatures of benthic habitats. Different studies (Vahtmäe *et al.* 2006; Kutser *et al.* 2006a) show that small variations in water depth (the distance that light has to travel to and from the substrate) have a significant impact on the possibility to recognise different bottom types. Besides, viewing water bodies under angles other than nadir can increase the amount of sun and sky glint significantly. For these reasons the use of multiangular images was excluded from this study.

The processing of CHRIS images is not as well developed as the sensors previously cited. In this study, the first two bands (411 and 442 nm, respectively) were ruled out due to the problem that the atmospheric correction algorithm was not effective. Bands W17 (872 nm) and W18

(1019 nm) were also eliminated from the analysis taken into account the strong absorption of radiation by water molecules in the near infrared part of electromagnetic spectrum (NIR). After atmospheric correction unusual values appeared in water zones in the bands: W4 (510 nm), W6 (561 nm), W8 (590 nm), W11 (672 nm) and W13 (686 nm). This issue was also reported by authors such as Ruíz-Verdú *et al.*, (2005) and Alonso *et al.*, (2009) who recognised the difficulty to process CHRIS data to Level 2. The high values present in these bands could be explained by sensor calibration problems due to these values affect the same bands in the three analysed images. Land reflectance values are higher than water values for this reason this spectral distortions were not appreciable.

Maximum Likelihood classifier shows high values of overall accuracy and kappa coefficient, higher than 90% and 0.87 respectively, indicating a good general classification. As it was shown in the confusion matrices, all established benthic types were correctly classified as well. These types reach percentages around 90% or even higher indicating a high correlation between image results and validating areas. 23/09/2008 and 02/12/2008 images show a little confusion between *macroalgae less than 5 m* and *deep submerged sand* classes, decreasing accuracy percentages to around 80% and 74% respectively, that could be explained by commission and omission errors. Results obtained in this classification are similar to the obtained by Casal *et al.* (2011) using SPOT-4 images for the same study zone where the percentages higher than 70% were obtained in classification of the benthic substrates (seaweeds, emerged sand, submerged sand and emerged rock). However, depth differentiation between macroalgae was added in CHRIS images classification.

SAM classification was used to map different macroalgal groups (green, brown and red). Prior to this analysis a continuum removal procedure was carried out. This analysis shows that CHRIS bands used in this study are not sufficient to separate red macroalgae from brown macroalgae based on their spectral signatures, even if the macroalgae are not covered with water. This result is similar to those of Kutser *et al.* (2006b) for multispectral sensors like Landsat or IKONOS. The same authors declare that the spectral resolution of MERIS is sufficient to separate the three macroalgae groups (green, brown and red). However, its spatial resolution could be a limiting factor for mapping benthic habitats because of areas occupied by macroalgal belts comparable in size with MERIS full resolution pixel are rare. Comparing the spectral configuration of CHRIS mode 2 and MERIS it can be observed that CHRIS sensor has 14 spectral bands between 400 and 750 nm while MERIS has only 9 bands. Better spectral resolution and much better spatial resolution allows to expect that CHRIS sensor mode 2 was more suitable than MERIS to map macroalgae communities. However, spectral problems in some bands of CHRIS in this study did not let the maximal exploitation of its spectral capabilities.

In this study, attempt to classify three broad groups of macroalgae gave as result that the main benthic cover in shallower than 5 m is brown algae and the main class in waters between 5 m and 10 m is red algae. This finding is not supported by the fieldwork and suggests that the main cause of this classification result is the water column effect.

Concerning green macroalgae, only isolated pixels appear in SAM classifications. The lack of field information just in these positions does not allow validating these results. However, it is supported by field observations because green algae do not form large homogenous cover belts in the study area. Theoretically, this macroalgal group is relatively easy of differentiate from red and brown seaweeds as it was showed by our continuum removal analysis. Moreover, Vahtmäe *et al.* (2006) carried out some bio-optical modelling and reported that green macroalgae could be separated from deep water by hyperspectral remote sensing until 7 m depth and from red and brown algae and sand until 8 m depth.

Results reached in this study show that CHRIS spatial resolution is not sufficient to map in detail the different macroalgal groups because the benthic cover is quite heterogeneous. Similar results were also reported, using multispectral and hyperspectral sensors, by authors such as Andréfouët *et al.* (2004), Vahtmäe and Kutser (2007) or Ashraf *et al.* (2010) who affirm that spatial resolution is a significant factor which influences the accuracy of submerged vegetation mapping. In the study zone only some species of brown macroalgae cover areas large enough to compare with CHRIS pixel size. Green and red macroalgae do not usually form homogeneous belts in the study area and their patches use to be smaller than CHRIS pixels size. This demonstrates that spatial resolution is very important in remote sensing of coastal waters (Barnsley *et al.*, 2004). For this reason, CHRIS could be considered a suboptimal sensor to map heterogeneous macroalgal patches.

The spectral signatures of each macroalgal group (green, brown and red) are consistent all over the world (Maritorena *et al.*, 1994; Kutser *et al.*, 2003; Dekker *et al.*, 2005; Kutser *et al.*, 2006c). In this way, CHRIS sensor could be applied to mapping macroalgal communities in other places where homogenous assemblages of macroalge are larger than CHRIS spatial resolution.

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CHAPTER IV

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ASSESSMENT OF AHS (Airborne Hyperspectral Scanner) SENSOR TO MAP MACROALGAL COMMUNITIES ON THE RÍA DE VIGO AND RÍA DE ALDÁN COAST (NW SPAIN)

ABSTRACT

Ría de Vigo and Ría de Aldán have high biological richness that is reflected in the number of environmental protection areas like the Atlantic Islands National Park and five places of community interest (LICs). Benthic algal communities play an important role in these ecosystems due to their ecological functions and support a great part of this biological richness. We tested by means of bio-optical modelling and Airborne Hyperspectral Scanner (AHS) images to what extent remote sensing could be used to map these communities in Ría de Vigo and Ría de Aldán (NW Spain). Reflectance spectra of dominating macroalgae groups were modelled for different water depths in order to estimate the separability between different bottom types based on their spectral signatures and the spectral characteristics of the AHS. Our results indicate that separation between three macroalgae groups (green, brown and red) as well as sand is possible when the bottoms are emerged during low tide. The spectra differences decrease rapidly with increasing water depth. Two types of classifications were carried out with the three AHS images: Maximum Likelihood and Spectral Angle Mapper (SAM). Maximum Likelihood showed positive results reaching overall accuracy percentages higher than 95% and kappa coefficients higher than 0.90 for the bottom classes: *shallow sand*, *deep sand*, *emerged rock*, *emerged macroalgae* and *submerged macroalgae*. Sand and algae substrates were then separately analysed with SAM. These classifications showed positive results for differentiation between green and brown macroalgae until 5 m depth and high differences between all macroalgae and sandy substrate. However, differences between red and brown macroalgae are only detectable when the algae are emerged.

Keywords: hyperspectral, AHS, macroalgae, benthic mapping, coastal zone

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1.INTRODUCTION

Benthic algal communities play an important role in coastal ecosystems due to their ecological functions. These communities are essential for many organisms as habitat (e.g. Cacabelos *et al*. 2010), mating and nursery grounds (e.g. Shaffer 2003), feeding areas (e.g. Lorentsen *et al*. 2004) and refuge (e.g. Gotceitas *et al*. 1997). Another relevant aspect is their important contribution to primary production (Mohammed and Fredriksen 2004), the sediment stabilization and coastline protection (Madsen *et al*. 2001), besides being a suitable indicator on the ecological status of coastal communities (Juanes *et al*. 2008). On the other hand, the interest of commercial use of some algal species has been increased during the last years in many parts of the world (e.g. Vasquez 2008; Vea and Ask 2011). The same situation is also found on the Galician coast (Cremades *et al.* 2004) where specific exploitation plans were established.

In this zone the three main groups of macroalgae, Chlorophyta, Phaeophyta and Rhodophyta (green, brown and red macroalgae respectively), are represented. Each of these groups has characteristic pigments that involve different optical properties that could be used for separation between the benthic algae. All of them contain chlorophyll-a, but the presence of other chlorophylls and accessory pigments is varying (Hedley and Mumby, 2002). Chlorophyll-a has absorption peaks at around 435 and 675 nm (Haxo and Blinks, 1950). Chlorophyta contain also characteristic pigments such as chlorophyll-b that absorbs at around 480 and 650 nm and β-carotene that absorbs at around 427, 449 and 475 nm (Hedley and Mumby, 2002). On the other hand, Phaeophyta contain chlorophyll-c that has absorption peaks at around 460 and 633 nm (Beach et al., 1997), β-carotene and xanthophylls like fucoxanthin that absorbs around 426, 449 and 465 nm (Hedley and Mumby, 2002). Because of the dominance of the accessory pigments these algae are brown in colour rather than green (due to their higher absorption in the green waveband). Rhodophyta are characterized by the presence of β-caroterene and mainly α-carotene which has absorption peaks at around 423, 444 and 475 nm (Hedley and Mumby, 2002). Red algae contain also biliproteins which are divided into the phycoerythrins, phycocyanins and allophycocyanins. The phycoerythrin has an absorption peak at around 543-568 nm, phycocyanin has absorption peaks at around 553 and 618 nm (Smith and Alberte, 1994) and allophycocyanin at around 654 nm (Hedley and Mumby, 2002). The exact location of each characteristic pigment absorption peaks can vary slightly from one study to another depending on the measurement conditions (in solvents or in vivo), the physiological state of macroalgae, etc.

Due to their ecological and economic importance, there is a strong need for methods that allow collecting quantitative and qualitative information about benthic communities, in order to allow their efficient assessment, monitoring and management. The use of remote sensing for this purpose has certain advantages: the method is non-invasive, allows studying large areas, mapping inaccessible zones as well as provides the possibility of repetitive cover of a target area. Besides, this method is faster and less costly than conventional field methods (diving, grab samples, video). Due to these advantages multispectral and hyperspectral sensors have been used successfully in many studies to map benthic algal communities (e.g. Kutser *et al*. 2006a; Bertels *et al*. 2008; Casal *et al*. 2011). However, zones with diversity of habitats, like the Galician coast, suggest the need for using high spatial and spectral resolution sensors to map benthic habitats in detail.

The original definition for imaging spectrometry or hyperspectral imaging was proposed by Goetz *et al*. (1985) as the acquisition of images in hundreds and contiguous spectral bands such that for each pixel a radiance spectrum can be derived. These characteristics present an advantage compared to multispectral image increasing the number of possible applications and the amount of information that can be retrieved from the imagery. The current airborne sensors can cover a wide spectral range (400-2500 nm) with high spectral resolution (a few nanometers) as well as an eye-catching spatial resolution (0.5 m or less). The major benefit of airborne remote sensing, compared to satellite-based systems, is that the user can define the deployment and operational characteristics of the remote sensing system. In general, an airborne system can be deployed when atmospheric (i.e., cloud-free), environmental and solar conditions are acceptable to study a specific phenomenon (Myers and Miller 2005). The deployment can also be coordinated with a field program to acquire *in situ* measurements for instrument calibration, algorithm development or validation. On the other hand, this flexibility of user-defined deployments provides a capability to study short time (hours to days) coastal events such as algal blooms, spills or floods that are usually difficult to study by most satellite-based systems.

One of the major obstacles in remote sensing mapping of benthic habitats is the influence of the water column on the measured signal. For this reason most of benthic mapping work has been carried out in clear waters (e.g. Andrefouet *et al*. 2004; Phinn *et al*. 2008; Szekielda *et al*. 2010). However, the number of hyperspectral airborne studies carried out in water with high optical complexity in order to map benthic habitats is lower. Some examples include Pe´eri *et al*. (2009) who mapped macroalgae and eelgrass in the Great Bay Estuary using AISA sensor; Hening *et al.* (2007) and Mehrtens *et al*. (2009) who mapped rocky intertidal zone in Helgoland coast using ROSIS and AISA sensors respectively; Theriault et al. (2006) who mapped invasive species using CASI sensor or Alberotanza *et* a*l*. (1999) who mapped submerged vegetation in lakes using MIVIS sensor as well as Hunter *et al*. (2010) who used CASI sensor for the same purpose. There are also some examples of using CASI for benthic habitat mapping in the turbid coastal waters of the Baltic Sea (Kutser *et al*. 2009).

On the other hand, light conditions in water are important for primary production, species composition and submerged vegetation distribution but also, in monitoring water quality and interpretation of remote sensing images. Optically active substances determine the penetration of light into the water column and consequently the light available for bio-chemical processes inside of water and detectable by optical instruments or remote sensors (Reinart *et al*. 2004). In order to complement traditional water sampling, bio-optical models could be used to create synthetic data sets, which can later be used in the characterization of light climate in water (Morel *et al*. 2002), to elaborate remote sensing algorithms (Jupp *et al*. 1994; Pierson and Strömbeck 2000; Kutser 2004), map benthic habitats (Kutser et al. 2006a) or to be used in general ecological models (Xu *et al*. 2001).

In Spain, the National Institute for Aerospace Technology (INTA) supports airborne campaigns and offers among their instrumentation the Airborne Hyperespectral Scanner (AHS). This sensor is applied with success in the terrestrial zone, especially in studies related to agriculture (Jiménez *et al*. 2005 or Corbari *et al*. 2010). However, no reference was found in Spain or other parts of the world about testing AHS images in coastal environments neither for water quality mapping nor shallow benthic habitat mapping. Taking into account this background the present study has two goals: 1) to test whether the AHS imagery can be used for mapping macroalgal distribution; 2) to study the possibility of differentiation between different benthic algae based on their optical signatures.

2. MATERIAL AND METHODS

2.1. Study area

The study area was defined by the cover of the hyperspectral flight and corresponds with part of the Ría de Vigo and Ría de Aldán (NW Spain). Both Rías form part of the Galician Rías Baixas, and are located in the north-western of Iberian Peninsula (Fig. 1). The Ría de Vigo corresponds with the southern position of Galician Rías and has a SW-NE orientation. It has funnel morphology and a mean depth of 28 m varying from 52 m in the mouth to a few centimetres on the sandbanks at the head of the estuary (Montero *et al*. 1999). Following Nogueria and Ríos (1997) the Ría de Vigo can be divided into three zones, the innermost zone includes San Simón Bay and shows the characteristics of a typical estuary, due to the effects of tides and the influence of the Oitaven River. The middle zone, which spreads from Rande Strait to Cape Mar, is under the influence of both continental and oceanic contributions and finally, the outermost zone that is under dominant oceanic influence, includes the area lying between Cape Mar and Cíes Islands. On the other hand, the Ría de Aldán is a short ría (7 km) and relatively deep (40 m) oriented NNW whose mouth, 3.5 km-wide, borders the external southern part of Ría de Pontevedra (León *et al*. 2004). Both zones present a semidiurnal tidal regime with a tidal range around ~4 m.

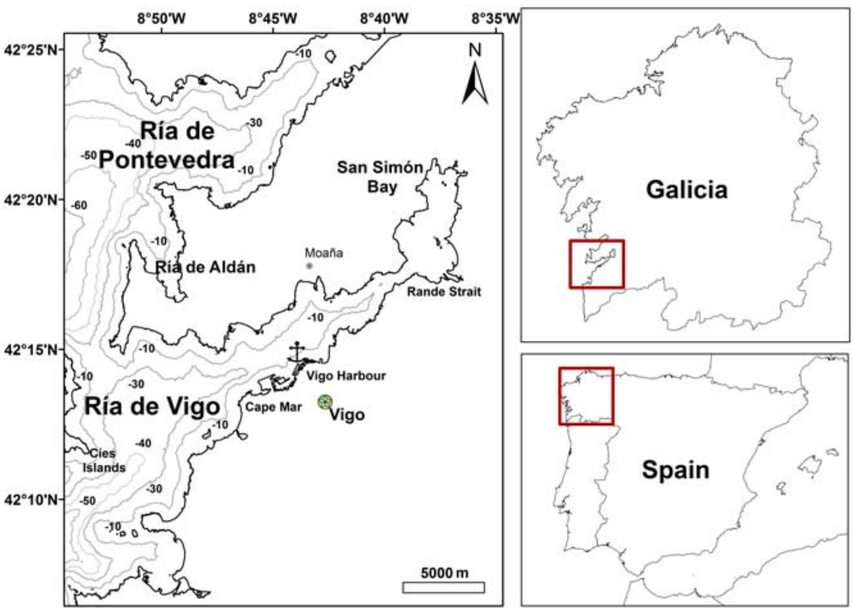

Fig.1. The study zone was located in the Ría de Vigo and Ría de Aldán (NW Spain). The grey lines in the map indicate water depths between 10 and 60 m.

Mussel culture is the main aquaculture activity, conducted on floating rafts that form several polygons occupying ~5% of the Ría's surface. However, in a recent study carried out by Alonso-Pérez *et al*. (2010) was not detected any significant alteration in the water column biogeochemistry associated to the mussel farming. This fact could be result of the upwelling dynamic system due to both study zones, Ría de Vigo and Ría de Aldán, are located in an upwelling system. The upwelling system is related to the northerly winds from March to September that promotes a massive response of phytoplankton productivity inside the Rías ~1.4 $gCm^{-2}d^{-1}$ during upwelling season (Figueiras *et al*. 2002) and with nutrients being responsible of the high productivity of these zones. The extension and intensity of seasonal upwelling and downwelling favourable periods vary strongly from year to year.

Most part of the coast present in Ría de Vigo and Ría de Aldán correspond with sheltered or semi-exposed. Sand is alternated with rocky substrate covered with a wide diversity of seaweeds. It should be mentioned that only seaweeds that are able to form big (larger than pixel size) homogeneous patches are identifiable from the remote sensing point of view. On the other hand seaweeds that do not form this kind of assemblages or are located as basal stratum of others with greater size cannot be mapped with remote sensing. In both study zones, rocky intertidal areas are dominated by brown macroalgae belts. The most typical seaweeds are: *Pelvetia canaliculata*, *Fucus spiralis*, *Fucus vesiculosus*, *Bifurcaria bifurcata* and *Ascophyllum nodosum*. In some places red macroalgae such as *Mastocarpus stellatus*, *Caulacanthus ustulatus*, *Chondracanthus* sp., *Gigartina pistillata* and *Chondrus crispus* form caespitose communities underneath the cover of different intertidal *Fucaceae* but their presence is less common than brown macroalgae. In some tidal basins that appear in low tide it is also common to find some green macroalgae like *Entheromorpha* sp.

The subtidal zone is dominated by large brown macroalgae that can cover extensive areas such as *Laminaria saccharina*, *Laminaria ochroleuca*, *Laminaria hyperborea*, *Saccorhiza polyschides*, *Halydris siliquosa*, *Himantalia elongata*, *Cystoseira baccata* and the invasive seaweed *Sargassum muticum*. Red macroalgae are smaller in size and are usually located on basal substrate of brown macroalgae and it is less common to find subtidal homogenous patches. The most characteristic red macroalgae in subtidal zone are *Asparagopsis armata*, *Gracilaria multipartita*, *Gracilaria gracilis***,** *Gelidium spinosum* and *Rhodymenia pseudopalmata*. In protected areas of the medium/lower intertidal and upper subtidal zones are characteristic large homogeneous assemblages of *Ulva* sp. and seagrasses of *Zostera marina* and *Zostera noltii*. In more exposed zones the presence of homogeneous patches form by *Codium tomentosum* is also typical. The description of the macroalgal communities present in the study area was made based on studies carried out by John (1971), Bárbara and Cremades (1993), Veiga-Villar (1999), Cremades *et al*. (2004), Olabarria *et al*. (2009), Filgueira and Castro (2010), among others, as well as personal observations.

2.2. Field data

Field data consisted in radiometric measurements and seaweed abundance in the intertidal and subtidal zone.

2.2.1 Radiometric measurements

Three spectroradiometers were used to collect irradiance and reflectance data: an ASD FieldSpec FR spectroradiometer with a spectral range from 350 to 2500 nm (sample interval of 1 nm) and two Ocean Optics USB2000 spectroradiometers with a spectral range from 350 to 1100 nm (sample interval of 0.5 nm). The ASD FieldSpec FR was fixed to the bow of the boat used during the field work, avoiding the possible influence of the boat shadow. The support consisted of a metallic curved axis and a platen that allows controlling the azimuth angle through the projection of the shadow according to its orientation to the sun. Over the metallic axis were fixed the optical fibre and a Lambertian surface of 25% reflectance to calibrate the measurements. Measurements were made during the central daylight hours to keep solar illumination conditions as similar as possible. The polar (θ) and azimuth (φ) directions were $\theta \approx 40^{\circ}$ from the nadir and $\varphi \approx 135^{\circ}$ from the sun, these directions would minimize the effects of sun glint and non-uniform sky radiance (Mobley, 1999). In this way, the solar irradiance (E_s), radiance of the light reflected from the water (L_{sfc}) and diffuse sky radiance (L_{sky}) were measured with $\theta \approx 40º$. The optical fibre field of view (FOV) was 25º but adapted to 8º, following the NASA established protocols for oceanic studies (Fargion and Mueller, 2000; Domínguez-Gómez *et al*. 2009). Duration of the measurements in each point was less than one minute guaranteeing the minimum illumination variation.

Upward (E_u) and downward irradiance (E_d) were measured at different depths using two underwater cosine receptors placed in a "T" support, with an orientation of 180º each other, and connected to the Ocean Optics spectroradiometers through two optical fibres. The support was covered with black adhesive tape to eliminate any interference with measurements. Besides, a plumb was placed in the ends to reduce the movement with water current obtaining a measurement as perpendicular as possible to the water surface. Measurements were made with 0.5 m or 1 m intervals depending on the depth. Radiometric measurements were carried out in the days previous, during and after the hyperspectral flight. In each field point ancillary data as GPS position, wind speed, depth, bottom visibility, video and photographs were recorded.

Reflectance of some seaweeds species and sand was also measured in their natural environment without water column influence. These measurements were carried out using the ASD FieldSpec FR spectroradiometer and calibrated by a Lambertian surface of 99% reflectance (white reference standard). Thus, spectra of green macroalgae species (n=6), brown macroalgae species (n=15), red macroalgae species (n=12) as well as sand (n=8) were measured. These reflectance spectra were used in bio-optical modelling in order to determine separability of different bottom types.

2.2.2 Seaweeds abundance

Abundance of seaweeds species in the intertidal and subtidal zones was also estimated to complement radiometric measurements. This information was used to characterize in detail the presence of species in the study area and establish training and validating areas for image classification. Measurement points were established over rocky substrate along the zone where the hyperspectral flight was planned. In each point, abundance of all species present was estimated using 50 x 50 cm quadrats and the percentage of cover was recorded in eleven classes (absent and cover percentages from 10% to 100%). In addition to the quadrats information GPS coordinates and photographs were also taken. During field work, data from 124 intertidal points and 20 subtidal points between 1.5 and 11 m were collected along the study area (Fig. 2).

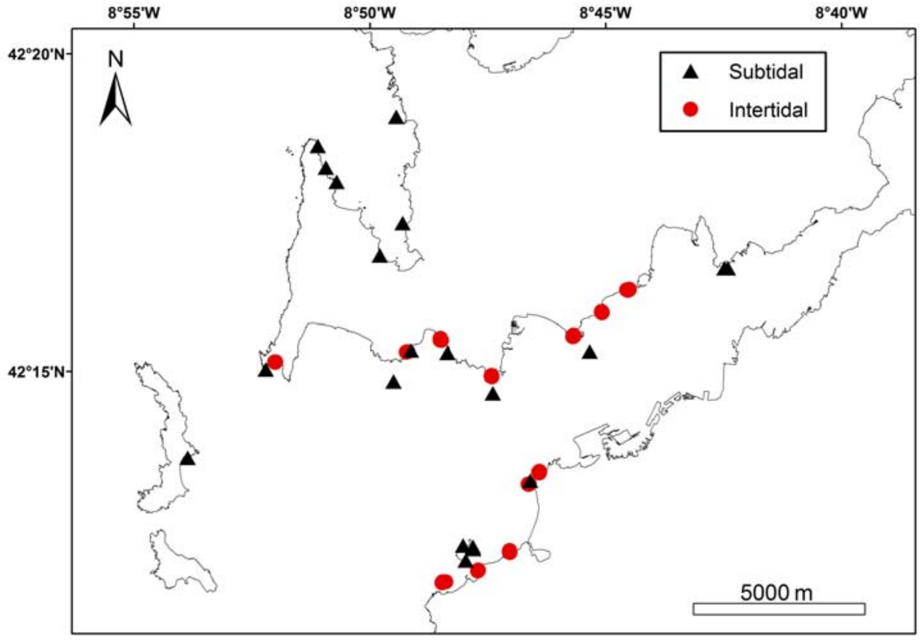

Fig.2. Locations of macroalgae abundance measurements. Several quadrats (50x50 cm) were measured in each site.

2.3 Bio-Optical modelling

Inherent optical properties of water, water depth and bottom type are the main physical parameters determining the signal detectable by remote sensing sensors. We used a simple model developed by Maritorena *et al*. (1994) to study influence of water depth on shallow water reflectance spectra:

$$R(0,z) = R_{\infty} + \left(R_b - R_{\infty}\right)\exp(-2Kz)$$

where z corresponds to bottom depth (m), R_b to the bottom reflectance and R_∞ with reflectance of optically deep water. The operational attenuation coefficient, *K*, represents attenuation of the downwelling stream, and the upwelling stream originating both from the bottom and from the water column (Maritorena *et al*. 1994). Following these authors we have considered the vertical diffuse attenuation coefficient (K_d) as a good approximation for *K*.

In this study, downward irradiance measurements were used to determine the K_d for each wavelength of AHS bands. Experimental determination of K_d, is possible only by radiation measurements *in situ*, however, these may be precluded because of weather conditions (Arst *et al*. 2002). In ocean optics, spectral K_d at a geometric depth is defined as (Gordon *et al*. 1980):

$$K_d(z) = -\frac{1}{E_d\left(z\right)}\frac{dE_d(z)}{dz}$$

where E_d (z) is spectral downwelling irradiance at depth *z* and *z* is pointing downward from the surface. K_d is an apparent optical property (AOP) (Preisendorfer 1976), which varies with the angular distribution of the light field (Kirk 1984). Since the light distribution changes with depth (Tyler 1960), K_d (z) varies with *z* even for vertically homogeneous waters before reaching an asymptotic values at greater depths (Liu *et al*. 2002).To know vertical variation of K_d (z), the E_d (z) needs to be measured within an infinitesimal range of z. In the field measurements of K_d, wave-introduced fluctuations in the subsurface light field and make it nearly impossible to accurately determine K_d (z) (Lee *et al*. 2005). To overcome this obstacle, a common and useful practice is to calculate the diffuse attenuation coefficient between the irradiances measured over distant depths and get with z_1 and z_2 far apart to ensure reliable measurements of E_d change (Lee *et al*. 2005).

$$K_d(z_1 \leftrightarrow z_2) = \frac{1}{\left(z_2 - z_1\right)}\ln\left(\frac{E_d(z_1)}{E_d(z_2)}\right)$$

To apply Maritorena *et al*. model the spectra measured in the field, without the water column influence, were resampled to the AHS wavelengths from 457 to 745 nm and the differences between reflectance at species level were analysed.

2.4 Remote sensing data

Hyperspectral flight using Airborne Hyperspectral Scanner (AHS) was carried out by the National Institute for Aerospace Technology (INTA) during the low tide. Aerial remote sensing data were obtained over Ría de Vigo and Ría de Aldán on 21st June 2008 between 7:46 and 10:21 hours UTC (8:46 and 11:21 local time).

The AHS sensor can register images in 80 bands between the visible and thermal spectral regions (Table 1). In the VIS/NIR range bands are relatively broad (28-30 nm), acting as a multispectral sensor, and its coverage is continuous from 430 nm to 1000 nm. In the SWIR range, there is an isolated band at 1600 nm. Next, there is a set of continuous, fairly narrow bands (13 nm) between 2000 and 2500 nm, which are well suited for soil/geologic studies (Fernández-Reanu *et al*. 2005). In the MIR and TIR ranges, spectral resolution is again low (30 to 50 nm), and the atmospheric windows (3000 to 5000 nm and 8000 to 13000 nm) are fully covered with 90º FOV and 2.5 mrad instantaneous field of view (IFOV) (Fernández-Renau *et al*. 2005).The imagery set was taken from CASA-212-200 airplane. Ten flight lines 18 km long and 2 km wide were flown with a radiometric resolution of 12 bits. The height of the flight was 975 m (3200 ft) above the ground level involving a 2.5 m pixel size.

Table 1. Spectral configuration of AHS sensor (Rejas et al., 2005). The last column represents the different spectrometers or ports where incident radiation is divided by AHS sensor.

Band	Spectral Limit		Spectral range	Spectral width (µm)	NER Est. @ 25 r.p.s. w. cm-2.nm-1.sr-1	Spectrometer
	Low (µm)	High (µm)				
1 a 20	0.43	1.030	VIR+NIR	2.0 E-08	2.00E-08	PORT#1
21	1.550	1.750	SWIR	1.0 E-08	1.00E-08	PORT#2A
22 a 65	1.994	2.450	SWIR	1.50E-08	1.50E-08	PORT#2
66 a 69	3.30	5.40	MIR	1.50	1.50	PORT#3
70 a 80	5.10	12.70	LWIR	1.00	1.00	PORT#4

Weather conditions were ideal at the beginning of the flight with clear sky and no wind. However, a dense fog started to cover the study area after the fifth flight line and the flight had to be cancelled. Taking into account the presence of clouds and a strong sun glint in the most external images only three flight lines collected in the middle part of the Ría de Vigo and Ría de Aldán were analysed in this study (Fig.3). The first flight line was also ruled out because of the low presence of seaweeds.

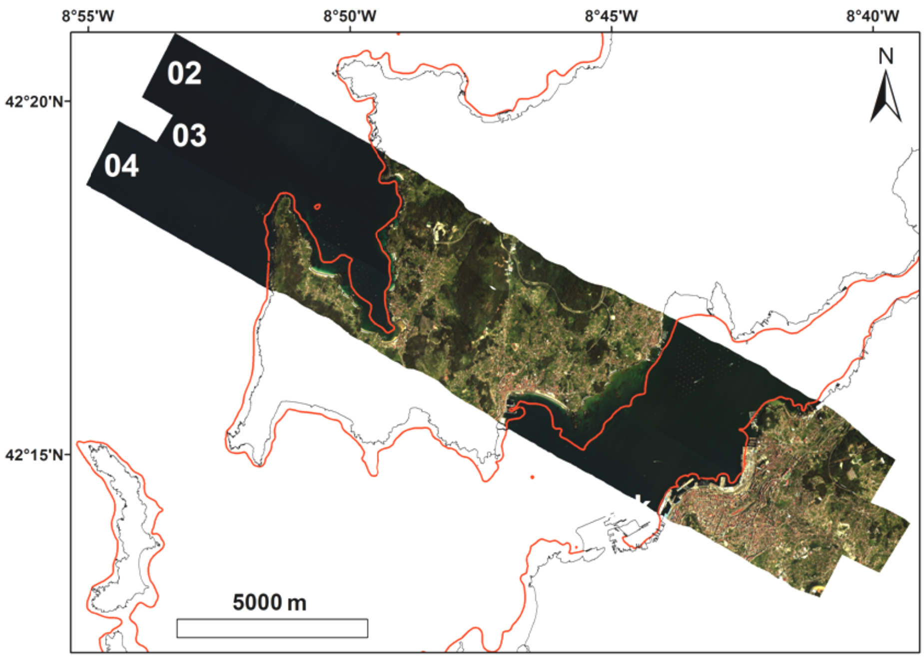

Fig.3. Three images (AHS flight lines) were analysed in this study. The red line corresponds to 5 m bathymetric line.

Before the analysis a pre-processing was applied separately to the three images. Radiometric correction was performed by the image provider INTA. AHS images were processed to at-sensor radiance using calibration coefficients obtained through an integrating sphere USS 4000. Movements of platform and AHS sensor, during images acquisition, introduce geometric distortions that only can be modelled through simultaneous registration of external orientation data (Rejas *et al.* 2005). During the flight campaign position data (X, Y, Z), pitch, roll and azimuth were registered through the inertial system POS/AV 410 of Applanix installed onboard the airplane. Images were orthorectified to the coordinate system UTM ED50 29N, through parametric correction using the direct geocodification PARGE software and a Digital Terrain Model (DTM) of 5 m pixel size.

Atmospheric correction was performed using ATCOR4 software by INTA. ATCOR is a method for atmospheric and topographic correction of remotely sensed optical imagery covering the solar spectral region (400-2500 nm) and thermal region (8000-14000 nm) (Richter 2004). It employs a database with the results of radiative transfer calculations based on the MODTRAN-4 code. Atmospheric correction is essential, especially in water zones. Inadequate atmospheric correction of coastal imagery inevitably leads to large uncertainties in the retrieved water constituents, as the water leaving radiance (the ‘‘useful’’ signal) is very low compared to the (perturbing) atmospheric ‘‘fingerprint’’ (Mélin and Zibordi 2005). This correction was validated through a comparison between spectra measured in field using ASD FieldSpec FR spectroradiometer and the ones obtained with AHS images at the same locations.

Eliminating all terrestrial features is useful when extracting aquatic information (Jensen *et al*. 1991). We masked out all land features, boats, piers and mussel rafts. The “land-mask” restricts the spectral range of brightness values to aquatic features and allows for detailed feature discrimination (Mishra *et al*. 2005). Besides a bathymetric mask, using the 5 m bathymetric line was applied taking into account the bio-optical modelling results regarding separability of different bottom types and the presence of sun glint in deep water areas.

Environmental noise was calculated to establish the minimum separation value between pairs of benthic spectra using the AHS images. The environmental noise equivalent delta radiance (NEDL) is defined as the amount of radiance at the sensor that produces a change in sensor output equal to the environmental noise level of the particular remote sensing system (Schott 1997). To calculate these values the method proposed by Dekker and Peters (1993) was followed. This method consists of sampling the standard deviation of the values in each band over a growing number of pixels (1x1, 3x3, 5x5, etc.) until the standard deviation reaches the first asymptotic limit. Critically, this sampling should be performed in an area “as homogenous as possible” in the image, so that the variations in signal due to image features do not contribute to the standard deviation (Brando and Dekker 2003). The values in each band at this first asymptotic limit are taken to represent the noise equivalents in the image. The choice of this method was made taking into account the recommendation of Wettle *et al*. (2004) for aquatic environments where low signal from water and submerged substrate targets is emanated.

2.5 Image analysis methods

Supervised image classifications can be divided into two broad groups: image based and physics based. Typically the image based approach is used when training areas are selected from the image (based on *in situ* data or local knowledge) and then used to classify the image. Another approach is using measured or modelled spectral libraries (look-up-tables) for image classification. The advantage of this method is that no *in situ* data is needed if the benthic habitats and water quality in the study area are known and the spectral library has been collected or produced before. This method also allows mapping water depth and bottom type simultaneously.

2.5.1. Image based classifications

Supervised parametric classifications were applied to the first 20 bands (456.7-1009.4 nm). Training areas were established for: emerged rock, shallow sand, deep sand, emerged macroalgae and submerged macroalgae using visual interpretation in RGB true colour composite, except for emerged macroalgae class where a colour CIR (colour infrared) composite was used.

Once the training areas were established, the separability between each class was analysed. In the three images all pairs showed values higher than 1.9 indicating a good separability between them (Richards 1999). These training areas were used in the supervised image classification, which was performed through parametric decision rules like Maximum Likelihood, Minimum distance and Mahalanobis distance included in ENVI software. To validate the obtained results, independent ground-truth areas were established using the same procedure as training areas (Table 2).

Table 2. Training and validating areas used to classify and validate AHS images using Maximum Likelihood classifier. Area is represented in number of pixels and m^2 for each class and AHS image.

		Emerged rock		**Shallow sand**		**Deep sand**		**Emerged macroalgae**		**Submerged macroalgae**	
		nº pixels	**m ^{2}**	**nº pixels**	**m^2**	**nº pixels**	**m^2**	**nº pixels**	**m^2**	**nº pixels**	**m^2**
Image 02	training	329	1316	187	748	658	2632	721	2884	714	2856
	validating	355	1420	226	904	780	3120	505	2020	904	3736
Imgae 03	training	308	1232	349	1396	1644	6576	866	3464	1372	5488
	validating	180	720	419	1676	1012	4048	462	1848	1615	6460
Image 04	training	47	188	1749	6996	2286	9144	2313	9252	2851	11404
	validating	130	520	1340	5360	2211	8844	1252	5012	6408	25632

For evaluating the accuracy of the classification a confusion matrix (error matrix) was prepared comparing the classification results on a category-by-category basis. An error matrix is a square array which expresses the number of sample units, in our case pixels, assigned to a particular category comparing results and validating areas (Congalton 1991). The kappa coefficient was also calculated to compare the accuracy of different classifiers. This coefficient is an indicator of overall agreement of a matrix. It measures the proportion of agreement after chance agreement has been removed from consideration (Cohen 1960). In this work to assess kappa coefficient the scale established by Landis and Koch (1997) was followed. These authors establish that: kappa ≤ 0 shows total disagreement, between 0.01 and 0.20 light agreement, between 0.41 and 0.60 moderate, between 0.61 and 0.80 high and between 0.81 and 1.00 total or nearly total agreement among diagnostics. Overall accuracy is computed by dividing the total correct (i.e. the sum of the major diagonal) by total number of pixels in the error matrix (Congalton 1991).

2.5.2 Spectral library approach

These classifications were carried out using Spectral Angle Mapper (SAM). SAM algorithm determines the similarity between two spectra by calculating the spectral similarity between them, expressed in α-values (Kruse *et al*. 1993). The α-value represents the angle difference between two spectral endmembers. The spectra are treated as vectors in a space with dimensionality equal to the number of spectral bands used (Kruse *et al*. 1993). This technique is relatively insensitive to illumination and albedo effects because the angle between two vectors is invariant with respect to the length of the vectors (Kruse *et al*. 1993). Different angles between 0.10 and 0.4 radians were tested following Kruse *et al*. (1993), Dekker *et al*. (2003) and Kutser *et al*. (2006a).

Results from the image based classifications were used to create a mask of shallow and deep sand, in order to analyse only areas covered with algae. Masks for submerged and emerged macroalgae were created as well. The three images were classified using SAM algorithm between 457 nm and 1000 nm for emerged and between 457 and 745 nm for submerged substrates taking into account the absorption of infrared and longer wavelengths by water molecules. The spectral library for emerged bottoms was created from our averaged field spectra resampled to the AHS wavelengths (see also modelling results below). The spectral library for classification of submerged algae was created using the bio-optical model. Reflectance spectra were simulated for different water depths down to 5 m with a range of 0.5 m. The results were compared with the field data collected during the image acquisition.

3. RESULTS

3.1 Bio-Optical modelling

The bio-optical modelling was carried out with two main purposes. Firstly we wanted to estimate what bottom types are separable from each other based on their optical signatures and secondly we needed the modelled spectral library for physic based classification of the AHS imagery.

Reflectance spectra of different macroalgae collected by us and the results of other authors from different parts of the world (Vahtmäe et al 2006, Kutser et al 2003, 2006a) indicate that separating benthic habitats on species level is practically not possible by means of optical signatures. For this reason the bio-optical model simulations were carried out for three broad groups of algae: green, brown and red macroalgae as well as emerged sand. An average spectrum was calculated for each group based on our field data. The number of average spectra was 6 for green, 15 for brown, 12 for red macroalgae and 8 for sand.

Separability of different bottoms (and deep water) from each other was studied following the procedure described in Vahtmäe *et al*. (2006). Differences between reflectance spectra were calculated and it was assumed that the bottoms are separable if the difference is higher than the environmental noise. Our results show that the algae groups are separable from each other if they are emerged during low tide (Fig. 4). Reflectance spectra of brown and red macroalgae are fairly similar and could be differentiated only at 572 and 716 nm bands. On the other hand, brown and green macroalgae are spectrally differentiable at 484, 543 and 745 nm and green and red macroalgae show spectral differences at 484, 543, 600, 716 and 745 nm. In both cases, the spectral differences are largest at 543 and 745 nm (Fig. 4B).

Spectral differences between deep water and emerged red, green and brown macroalgae, as well as sand were analysed. Differences between reflectance of all macroalgae groups and sand are high in all wavelengths (Fig. 4C). Red macroalgae and sand are spectrally well differentiable from deep water; however, the differences with sand are mainly due to its high reflectance. Regarding spectral difference of brown and green macroalgae, both macroalgae types present high values with respect to deep water (Fig.4D). Brown and deep water are differentiable from 484 to 629, 716 and 745 while differences of green macroalgae and deep water are located from 513 to 629, at 716 and at 745 nm. Both groups of macroalgae (green and brown) present the largest values in the green and red part of electromagnetic spectrum.

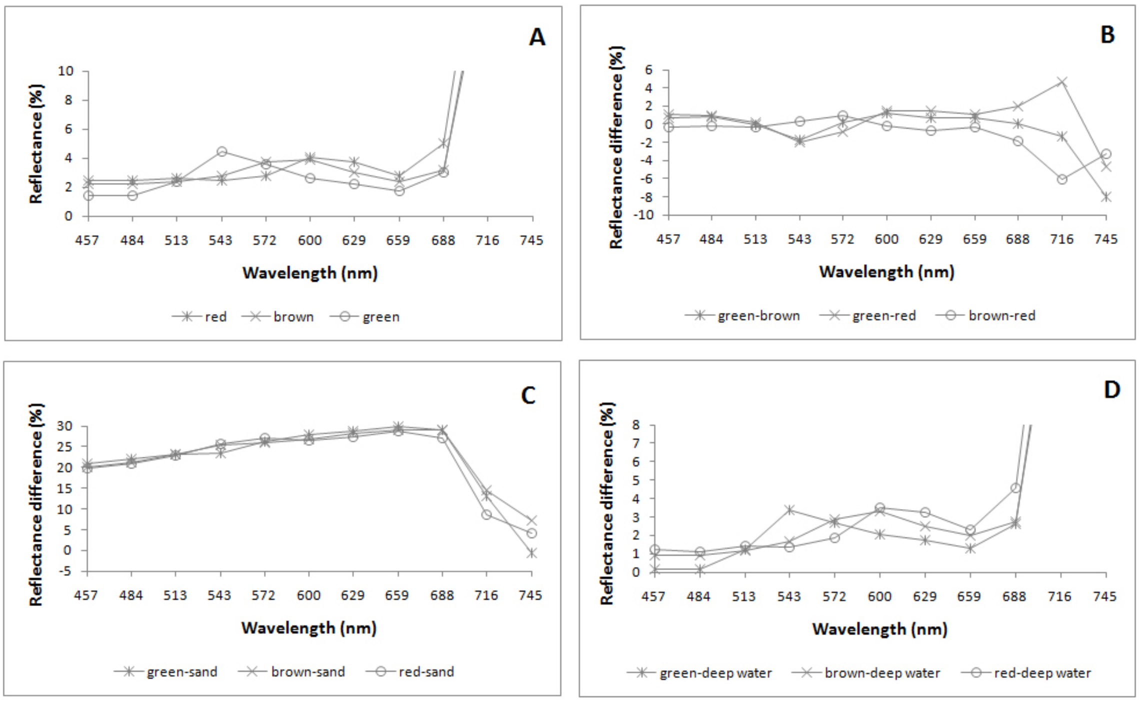

Fig.4. Reflectances of different bottom types and reflectance differences without water column influence. A) Reflectance spectra of green, brown and red macroalgae resampled to the AHS wavelengths. B) Reflectance difference between the three groups of macroalgae. C) Reflectance difference between macroalgal groups and sand. D) Reflectance difference between macroalgal groups and deep water. The wavelength range in the graphic A and D is shorter to be able to show important spectral features in visible part of spectrum.

Model simulations (Fig.5) show that green macroalgae are spectrally different from brown and red macroalgae at 543 nm band until 1 m depth (Fig.5B-C). On the other hand, brown and red macroalgae are not differentiable from each other if they are covered with water when AHS spectral bands are used (Fig5D). Differences between the three groups of macroalgae (green, brown and red) and sand show high values (Fig.5E). Spectral difference results show that all macroalgae groups are differentiable from sand at 484, 513 and 543 nm bands until 8 m depth. Differences of the three macroalgae groups with deep water decrease considerably due to the low reflectance of these classes with respect to sand (Fig.5F). Green macroalgae show spectral differences with deep water at 543 nm until 3 m depth. Brown algae show these differences at 543, 572 and 600 nm bands only until 1 m depth and red macroalgae show spectral differences with deep water at 513, 572, 600, 529, 716 and 745 nm bands until 0.5 m. Modelling results show that sandy bottom is differentiable from deep water at 484, 513 and 543 nm bands until 8 m depth.

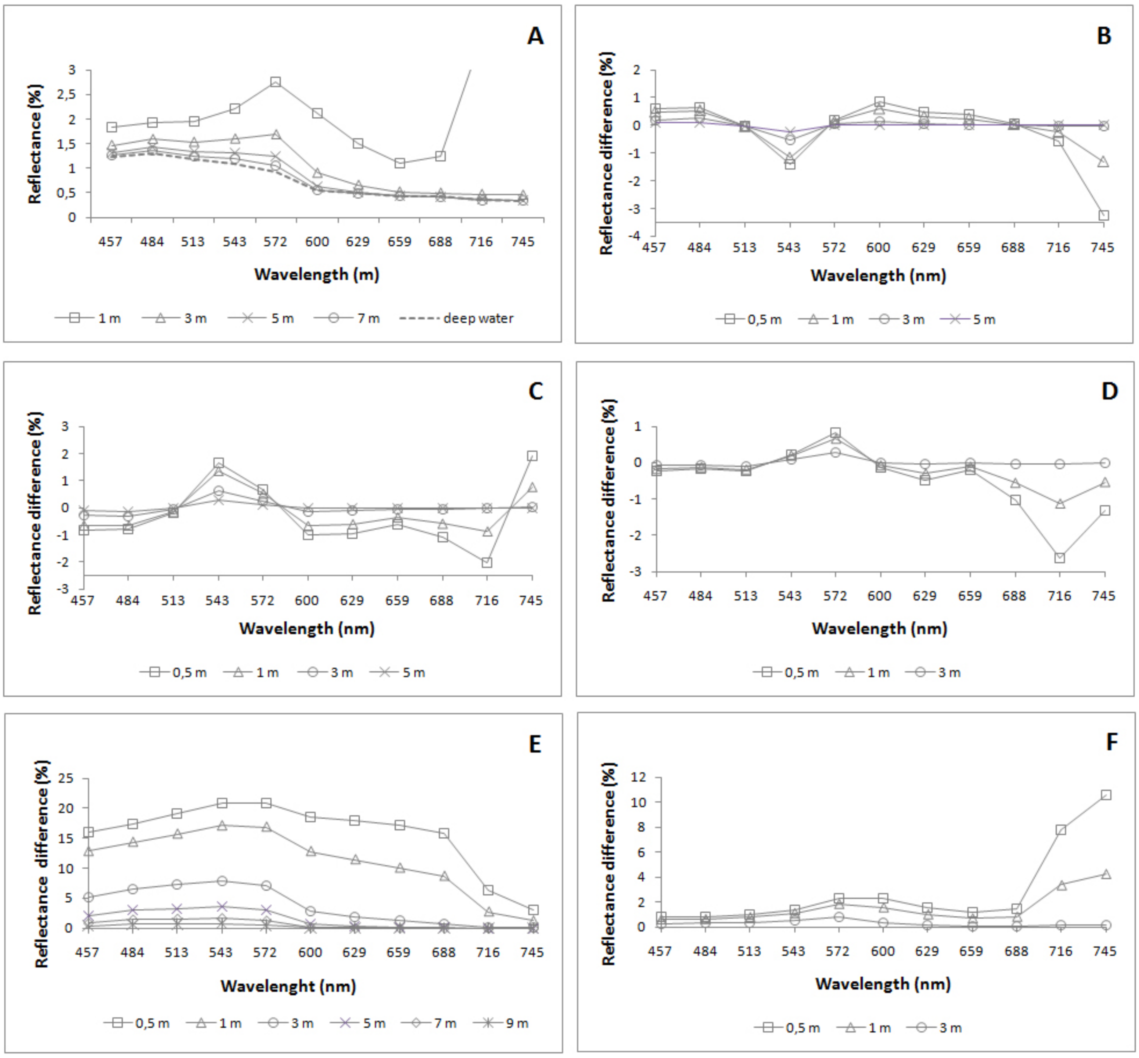

Fig.5. Spectral differences between simulated spectra at several water depths. A) Depth effect in a brown alga spectrum and its comparison with a deep water spectrum. B) Green and brown macroalgae. C) Green and red macroalgae. D) Brown and red macroalgae. E) Brown macroalgae and sand. F) Brown macroalgae and deep water.

The analysis of K_d used in the model for measured points (Fig. 6) showed higher values in all wavelength regions than the pure seawater, except for the last wavelength (745 nm). This can be attributed to the cumulative effect of absorption and scattering by phytoplankton cells, dissolved organic matter and suspended sediment present in coastal waters. Diffuse attenuation coefficient is the lowest at green wavelengths. Phytoplankton and coloured dissolved organic matter absorb light stronger at blue wavelengths and water molecules absorb strongly at red wavelengths. However, there are only three AHS bands (513, 543, 572 nm) in the green spectral region with the greatest penetration in depth and reflectance spectra of most benthic macroalgae are fairly similar in this part of spectrum.

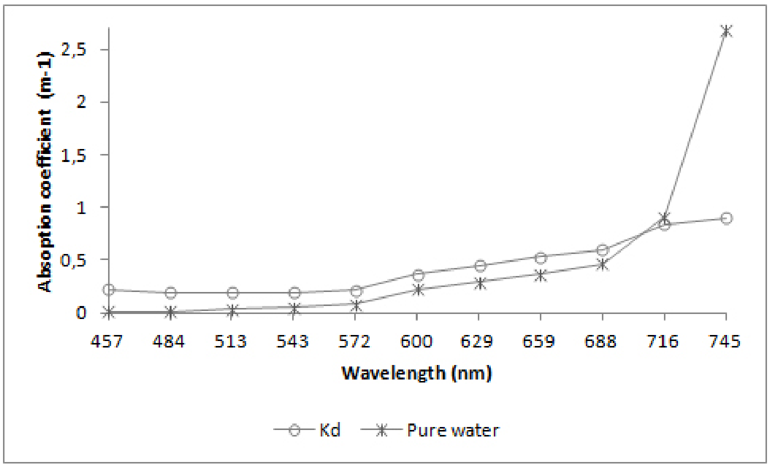

Fig.6. Average Kd measured near the coast in depth zone between 6.5 and 8.5 m and resampled to AHS wavelengths. The pure water absorption values presented here were taken from Buiteveld et al. (1994).

3.2 Image analysis

3.2.1 Image based approach

Our results show that the Maximum Likelihood classifier gave the best results from the three supervised classifications methods tested. Using this classifier overall accuracies of 95.09% (2655/2792 pixels), 95.21% (3737/3925 pixels) and 95.57% (7423/7608 pixels) and kappa coefficients of 0.93, 0.93 and 0.97 respectively, were obtained. According to the scale established by Landis and Koch (1997), these results indicate a total or nearly total agreement among diagnostics. Almost all classes present percentages higher than 90%, except for emerged rock where the percentage of agreement decrease to 24.81% in the image 04 indicating confusion between this class and emerged macroalgae and shallow sand. This confusion could be explained by the establishment of the training or validating areas because sometimes these substrates are located very close to each other. For example, emerged macroalgae appear over rocky substrate and, in some cases, it is difficult to separate them using visual interpretation.

3.2.2 Spectral library approach

After some experimentation we found that the classification of macroalgae gave the best results when sandy areas were masked out from the image. The sand mask was generated from the results obtained using the Maximum Likelihood method. Different angles in SAM were tested in order to find the best performing angle. The best results were obtained with 0.3 radians. In other cases either parts of the image remained unclassified or the classification results did not improve (using higher values).

Results obtained with SAM (Fig. 7 and Fig. 8) seem to be better in some cases than the predictions obtained from the bio-optical modelling. Analysing the classified images brown and green macroalgae seem to be differentiable until 5 m depth. However the scarcity of field data and the absence of a detailed bathymetric map do not let to assess accurately this result. The validation of these classifications were made using *in situ* observations at 11 subtidal points where a 100% of coincidence between classified images and field observations was found for the substrate type. Regarding the depth, 36% of the observations present coincidence with field observations and 36% present a difference of 1 m because the images and field observations were made in a different tide moment. This difference in depth is coherent with data acquisition due to depth values in the image are lower than the ones registered in the field. This fact could be explained due to the image acquisition was carried out during the low tide. Besides, a 27% (three points) present a depth difference higher than the typical tide range of the study area. These points are located in the deepest zones, close to the edge of the bathymetric mask. Thus, the errors could be caused by inaccuracy of the bathymetric data used like mask. For the 20 intertidal points, located in the analysed images, we observed a 50% of coincidence with regard to substrate type. The other 50% appears as unclassified in the image, probably due to the low density of vegetation that AHS sensor cannot register. Differences regarding to depth in the intertidal zone were also observed. These differences, as in the case of subtidal zone, could be explained by the different tide moment between image acquisition and field observations.

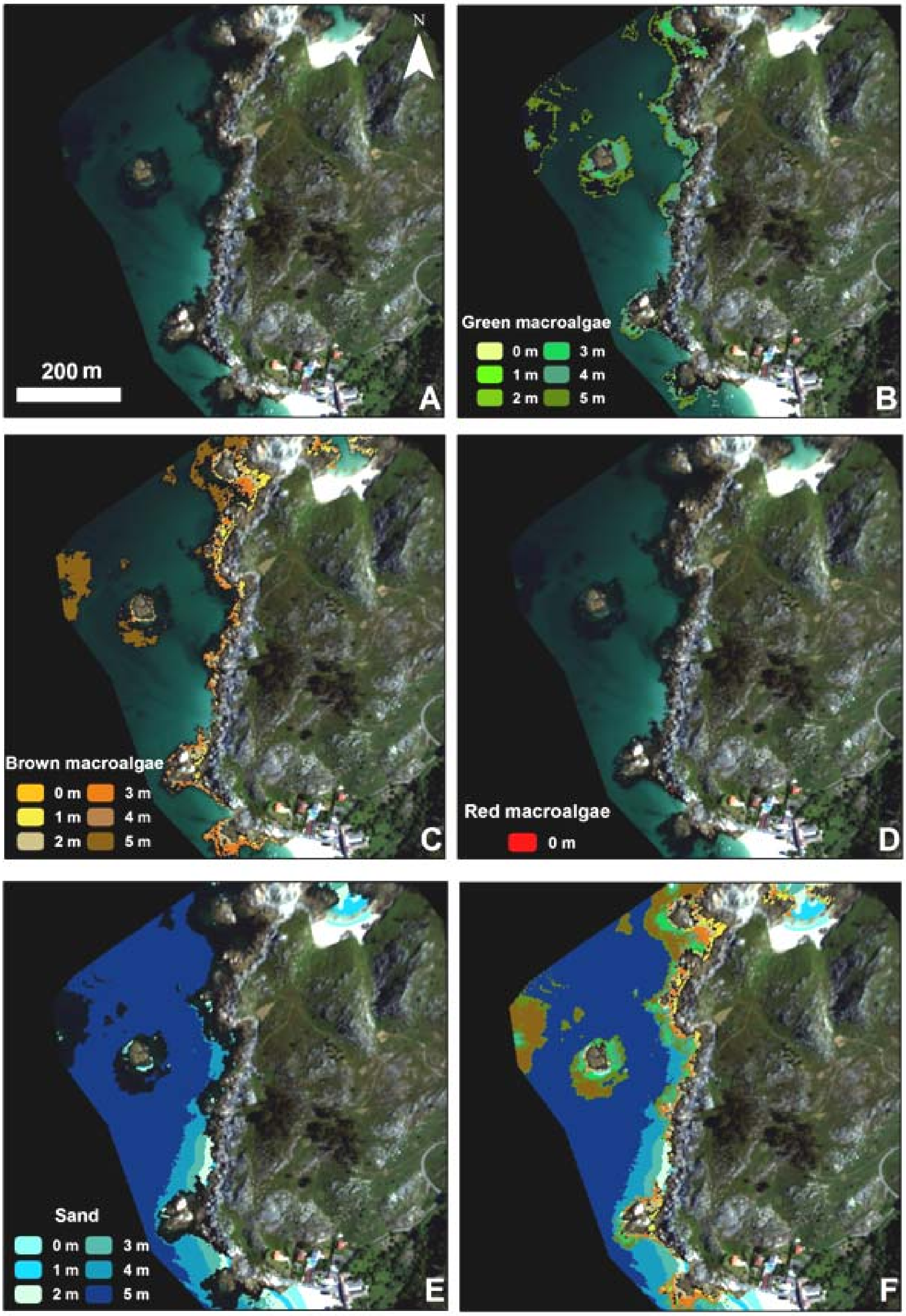

Fig.7. Fragments of AHS images classified with SAM for depth zone 0-5 m. A) AHS original image. B) Green macroalgae distribution. C) Brown macroalgae distribution. D) Red macroalgae distribution. E) Sand distribution. F) Fragment of AHS image showing all classes of SAM classification results until 5 m depth.

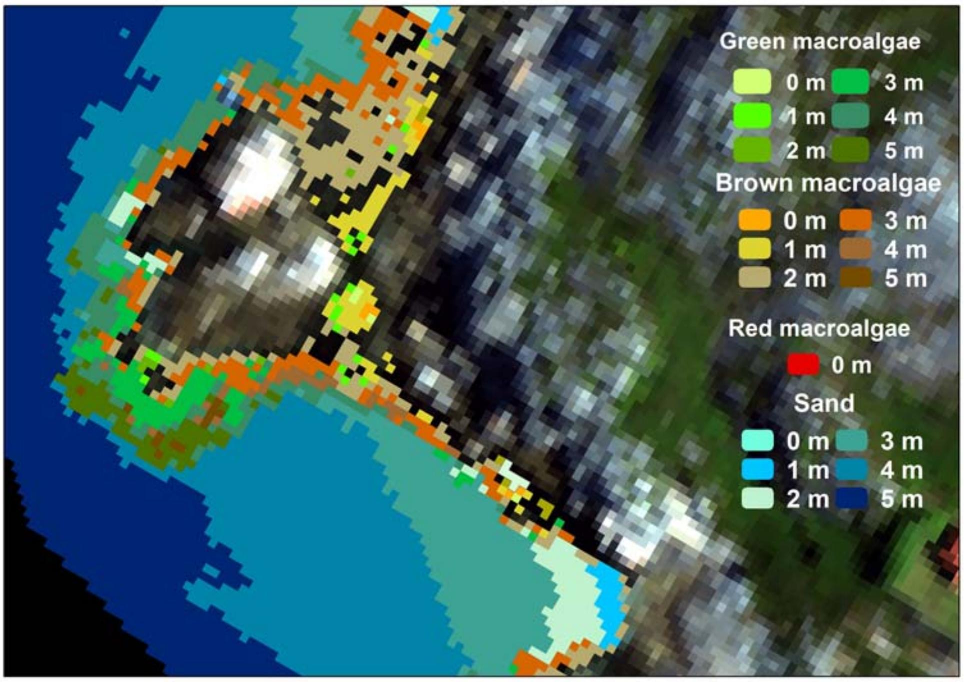

Fig. 8. Zoomed-in fragment of the benthic map obtained from the AHS imagery after SAM classifications.

4. DISCUSSION

Submerged aquatic vegetation is an important component of coastal ecosystems, playing a key role in the ecological functions of these environments. Surveys of these communities are commonly hindered by logistic problems and remote sensing represents a powerful alternative. However, aquatic plants and their properties are not as easily detectable as terrestrial vegetation due to the overlaying water column that causes a significant decrease in the spectral reflectance (Fyfe 2003; Pinnel *et al*. 2004), especially in the near-to mid-infrared regions where water absorption is stronger (Fyfe 2003; Silva *et al*. 2008). On the other hand in coastal waters, spectral scattering and absorption by phytoplankton, suspended organic and inorganic matter, as well as, dissolved organic substances also restrict the light passing to, and reflected from, the benthos (Dekker *et al*. 2001). To minimise the effects of the water column in the classifications a simple bio-optical modelling was carried out following the one established by Maritorena *et al*., (1994) and applied by different authors (Kutser et al. (2003); Dierssen *et al*. (2003) or Vahtmäe *et al*. (2006)). In this model spectra from green, brown and red macroalgae as well as sand, resampled to AHS wavelengths in the range from 457 to 745 nm, were modelled for several water depths.

Comparing green, brown and red macroalgae spectra measured by us and resampled to the AHS bands with those described by Maritorena *et al*. (1994), Kutser et al. (2006a, 2006b) and other published spectra of benthic algae, some differences in peaks and shoulders due to spectral resolution of AHS were found. For example, these authors describe a broad and prominent maximum at 550 nm for green macroalgae, however, this peak is shifted to 543 nm in AHS images due to the absence of 550 nm band. These authors also mention maximum values for brown macroalgae at 570-650 nm because of strong fucoxanthin (and carotene) absorption as well as the chlorophyll-c which absorbs at around 633 nm. This maximum also appears in the resampled spectra however, their location changed to 572 and 600 nm. Regarding red macroalgae the phycobilin pigments depressed their reflectance values in the green part of the spectrum, showing a common double peak pattern (600 and 650 nm) (Maritorena et al. 1994; Kutser *et al*. 2003, 2006a). Nevertheless, this double peak appears shifted to 600 and 629 nm in the spectra resampled to AHS image wavelengths. Lubin et al. (2001) also described a prominent dip around 570 nm, but it is barely negligible at 572 nm in AHS spectra. All macroalgae spectra analysed in this study show a shoulder at 659 nm attributable to different pigments in each group of algae. This shoulder can be explained by the presence of chlorophyll-b in green macroalgae (650 nm), fucoxanthin and chlorophyll-c in brown macroalgae (which present an absorption peak at around 645 and 659 respectively) and the presence of phycobilins that absorb at around 650-650 nm. On the other hand the shoulder present at 688 nm in all spectra could be explained by the absorption of chlorophyll-a present in all macroalgae. Regarding resampled sand spectrum, this is consistent in shape with spectra of the same substrate with more spectral resolution.

To compare the results obtained in our study to the ones obtained by Vahtmäe *et al.* (2006) using the same model in the Baltic Sea it is necessary to take into account the different water quality between both study areas. Vahtmäe *et al*. (2006) used three different water types in their modelling but to estimate the maximum depths where different macroalgae groups could be separable, the majority of results were presented for relatively clear open Baltic Sea water. These authors used as characteristics for this type of waters: 2 mg/m^3 of chlorophyll-*a*, 2 mg/L of total suspended matter and 1.5 m^{-1} absorption by CDOM at wavelength 400 nm . On the other hand, Lønborg et al. (2010) in surveys carried out on 26th June 2008 in the Ría de Vigo, close to our image acquisition, showed values of 4.32 mg/m^3 of chlorophyll-*a* and 0.37 m^{-1} absorption by CDOM at wavelength 350 nm while Alonso-Pérez et al. (2010) showed a concentration of 1.03 mg/L for total suspended particulate matter concentrations near the surface.

The comparison of simulations shows that green macroalgae and sand are differentiable from each other until 8 m in both water bodies. Brown macroalgae and sand are separable from each other down to 8 m according to our modelling results but Vahtmäe *et al*. (2006) showed that it can be done down to 11 m deep waters in the Baltic Sea. Both studies indicate that the separation of red and brown macroalgae is very difficult as the spectral differences between them are small and both algae are relatively dark. Ruling out these similarities, in general our results show lower maximum depths where different bottom types are separable. This difference could be explained by the higher chlorophyll concentration in Ría de Vigo and Ría de Aldán that could influence the water reflectance. On the other hand, both modelling studies used sensors with different technical parameters. Simulations carried out by Vahtmäe *et al.* (2006) used sensors like CASI and AVIRIS with better spectral resolution and SNR than the AHS sensor.

Results obtained using SAM algorithm show a high coherence in the type of substrates obtained with classifications and field observations in the three images. However the number of field observations coincident with the images is not too high as it was mentioned in the results part (11 points for subtidal and 20 for intertidal zone). Most of field data were collected in the outer part of the Ría where images were affected by clouds. Classifications of AHS images obtained with SAM showed that it is possible to differentiate three types of macroalgae (green, red and brown) when they are emerged being these differences extensible to sand substrate. On the other hand, brown and green macroalgae classification seems to be more promising than the modelling results indicated. Both substrates seem to be differentiable until 5 m depth. It could show that the method used to calculate the environmental noise was too conservative. Reflectance difference, calculated with modelled spectra for these substrates (brown and green macroalgae), shows a relatively high value at 543 nm until 5 m depth. This value could be the reason of the differentiation between the two substrates in classification image results. However, these differentiation values of useful signal could be preclude as noise by the noise environmental method used.

The depth estimation based on AHS images shows high correlation with field observations. Although, some exceptions appeared due to the different tide moment between field and image acquisitions or the low density of macroalgal cover that AHS sensor could not register. It is also observed some confusion in the image classification results between green macroalgae and sand despite of the modelling results indicate good separability. This occurs mainly in deep zones were sand is classified as green macroalgae. This fact could be explained two phenomena: algal film around sand particles and phytoplankton in the water column. The sand reflectance spectrum used in the modelling was collected over emerged sand on the beach. However, submerged sand is always covered by microalgae that affect the signal received by remote sensing sensors (Stephens *et al*. 2003). On the other hand, the high chlorophyll concentration present in the water column could also affect the obtained results. For this reason sand and macroalgae classification was carried out separately using masks created by Maximum Likelihood classifications results.

SAM interpretation results show that the emerged communities are predominantly formed by brown macroalgae (emerged intertidal belts and floating subtidal communities). In the classified imagery we observed quite large areas of green macroalgae in the upper subtidal zone. Some available field data indicates that there is *Ulva* sp. present in these areas. We also identified green macroalgae areas which are different from typical distribution of *Ulva* sp. canopy. These areas are located in a shallow and sandy zone. Because of the location and distribution we estimate that they could correspond to seagrass beds of *Zostera marina* and *Zostera noltii.* Presence of these species has already been described in the inner part of the Ría by several authors (Nombela and Vilas 1987; Filgueira and Castro 2010). However, the absence of field work in these locations and the lack of scientific references on the Moaña coast do not allow confirming that these areas are actually seagrass beds. Field observations indicate that *Codium tomentosum* was also present in more exposed zones. On the other hand, results of SAM classifications show that subtidal zones are dominated by the brown macroalgae species forming large assemblages.

We consider that the impossibility to differentiate between brown and red macroalgae in the subtidal zone is not a very important handicap on the Galician coast because of the macroalgae species composition in the area. Large size brown macroalgae dominate this zone in dense populations, as it is also shown in SAM classifications, and can reach 100% of coverage (John 1971). Red algae are only present as undergrowth that cannot be detected by remote sensing sensors. For this reason the results observed in the classified images (dominance of brown macroalgae in subtidal region) show high coherence with the field observations.

Up to now, studies on benthic macroalgae carried out on the Galician coast were based on traditional methods (transects, quadrates...) covering small areas. Proper large scale management of this area is not possible as the macroalgal cover data is available for certain smaller areas as well as the lack of continuous data in space and time. In this study we have shown that the AHS images present an advantage in the creation of accurate thematic maps of the shallow water benthic habitats in Ría de Vigo and Ría de Aldán. In spite of observing that AHS spectral resolution can be a limiting factor in the recognition of different macroalgae groups. However, the positive results encourage to test more accurate spectral sensors that can potentially provide even better differentiation between macroalgae communities and/or improve this capability in deeper waters.

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CHAPTER V

CHAPTER V

ASSESSMENT OF THE HYPERSPECTRAL SENSOR CASI -2 FOR MACROALGAE DISCRIMINATION ON THE RÍA DE VIGO COAST (NW SPAIN) USING FIELD SPECTROSCOPY AND MODELLED SPECTRAL LIBRARIES

ABSTRACT

Hyperspectral remote sensing constitutes an important tool in mapping shallow benthic habitats where high spectral and spatial resolutions are needed. However, the acquisition of hyperspectral images sometimes involves a high economic investment and there is no prior guarantee of their utility. Physics-based methods like bio-optical models are an alternative to assess sensors without purchasing the images. In this study, a simple bio-optical model for shallow water was performed to assess the use of the CASI-2 sensor for benthic macroalgal differentiation. For this purpose spectra of 17 macroalgal species were analysed. Uni- and multivariate statistical analyses were used to evaluate differences at species level showing that only a few species seem to be clearly differentiable: *Codium tomentosum*, *Laminaria saccharina* and *Corallina officinallis*. Thus, bio-optical modelling was performed for taxonomical groups presenting spectra that are consistent in shape. Using the CASI-2 sensor green, brown and red macroalgae as well as sand could be differentiated from each other when they are emerged. On the other hand, when substrates are submerged, the bio-optical simulations showed that using the CASI-2 sensor, the three macroalgal groups could be separated from each other until 4 m. Green and brown macroalgae were differentiable from deep water until 6 m whereas red macroalgae until 5 m. Macroalgal groups were separated from sandy bottoms until a depth of 10 m.

Keywords: hyperspectral, bio-optical model, macroalgae, benthic mapping, coastal zone

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1.INTRODUCTION

Coastal zones represent the transition between terrestrial and aquatic environments being one of the most dynamic and productive ecosystems on the Earth (Cicin-Sain, 2006; Yang 2008). The great diversity of coastal ecosystems turns these zones into an important source of food, habitat and refuge for many species as well as income supply for the coastal human population.

Macroalgal communities play an important role in the coastal environment and contribute to a great extent to the coastal productivity as it has been documented in the scientific literature. For example, it was reported that macroalgal communities contribute in an important way to the primary production (Mohammed and Fredriksen, 2004), are essential habitats (Birkettet al., 1998; Cacabelos *et al*. 2010), act as mating and nursery grounds (Borg *et al*. 1997; Shaffer 2003), feeding areas (Velando and Freire, 1999; Lorentsen *et al*. 2004) and as refuge (Bushmann 1990; Gotceitas *et al*. 1997) for many organisms. Another relevant aspect is their contribution in the sediment stabilization and coastline protection (Madsen *et al*. 2001), besides being a suitable indicator on the ecological status of coastal communities (Juanes *et al*. 2008).

Due to their ecological importance there is a strong need for methods that allow collecting quantitative and qualitative information about benthic communities for their efficient assessment, monitoring and management. Due to the complexity and dynamics of coastal environments, remote sensing appears as an alternative to conventional methods, based in direct observation, to study benthic habitats. Traditional field-based methods, like in-situ quadrats or line transects, are time consuming and cannot provide data over extensive areas. Digital remote sensing is the most cost-effective approach for acquiring such data (Mumby et al, 1999) and it is the only available tool to acquire data on a global scale (Hochberg et al. 2003). Moreover, remote sensing methods allow obtaining data with high temporal frequency as well as study inaccessible zones.

Hyperspectral sensors provide images in hundreds and contiguous spectral bands allowing the use of methods similar to those used in spectroscopy (e.g. derivative analysis, spectral modelling, matrix inversion) in the interpretation of remote sensing data (Kutser et al., 2003). The spectral range of these sensors can vary between 350 and 2500 nm as well as high spatial resolution (less than 1 m). These characteristics can be useful in heterogeneous environments as occur on the coast (Vahtmäe and Kutser 2007). Moreover, this technological advancement has raised new expectations about the possibilities for spectrally discriminating species. Terrestrial species discrimination has been highlighted as being one of the benefits of using hyperspectral data (Sobhan, 2007). Nevertheless, this discriminating ability depends largely on inter- and intra-species variability (Nagendra, 2002).

Remote sensing identification of marine vegetation at the species level has been difficult because the spatial resolution constraints the use of some of the available sensors (Kutser et al., 2006a; Casal et al., 2011). Furthermore, there is a little documentation about the reflectance properties of individual species in the different stages of the growth season and with regard to important phenological states (Ullah et al., 2000). One of the major obstacles in remote sensing mapping of benthic habitats is the influence of the water column on the measured signal. Therefore, most satellite sensors lack the sensitivity to discriminate spectra because they have a limited number of water-penetrating bands (Mumby et al., 2002). Due to the presence of relatively high concentrations of phytoplankton, suspended matter and dissolved matter in many coastal waters most of the benthic mapping work based on remote sensing has been carried out in clear (oceanic) waters. However, the number of hyperspectral studies in water with high optical complexity is increasing. Some examples include Pe´eri et al. (2008) who mapped macroalgae and eelgrass in the Great Bay Estuary using AISA sensor, Hening et al. (2007) and Mehrtens et al. (2009) who mapped rocky intertidal zone in Helgoland coast using ROSIS and AISA sensors respectively, Hunter et al. (2010) who used CASI sensor for mapping submerged vegetation in lakes or Vahtmäe at al. (2011) who mapped benthic vegetation and changes in coastal waters of the Baltic Sea.

Traditionally, when an imagery dataset is acquired, statistical analyses are used to group pixels into as many classes as are statistically significant (Kutser et al., 2003). To determine an appropriate class (e.g. sand, seaweed, rock, etc) training areas based on field work are established. Sometimes, it is also possible to infer classifications based only on the image information without having any ground truth data or using some preliminary knowledge about the study site (Kutser et al., 2003). However, another approach is possible using physics-based methods i.e. compare the modelled reflectance spectra with the reflectance spectra from remote sensing imagery. This approach has been used both in water quality monitoring (Arst and Kutser, 1994; Kutser et al. 2001; Dekker et al., 2002) and mapping of shallow water benthic habitats (Kutser et al. 2006a; Lesser and Mobley, 2007). In earlier versions of this approach modelling was carried out during the image interpretation while the most recent approach is to prepare a modelled spectral library before the image processing. Modelling a spectral library in advance is computationally more effective and allows using more accurate radiative transfer models. An advance due to the use of the physics-based methods in water quality remote sensing is that concentrations of all optically active constituents (phytoplankton, CDOM, suspended matter) can be retrieved simultaneously. Nowadays, there are also more comprehensive spectral libraries that include both water quality parameters and bottom parameters. For example, Brando et al. (2009) used an extensive spectral library that took into account bottom and water quality parameters and were able to retrieve all these parameters at the same time.

The objective of the present work is the assessment of the airborne hyperspectral sensor CASI-2 to discriminate macroalgal communities on the Ría de Vigo coast using a bio-optical model. The spectral separability between benthic substrates will be also analysed and a depth limit for their discrimination established.

2. MATERIAL AND METHODS

2.1 Study area

The Ría de Vigo (NW Spain) is located in the southern part of Galician Rías and has a SW-NE orientation (Fig.1). It has funnel morphology and a mean depth of 28 m varying from 52 m in the mouth to a few centimetres on the sandbanks at the head of the estuary (Montero *et al*. 1999). This zone has a semidiurnal tidal regime with a tidal range around ~4 m.

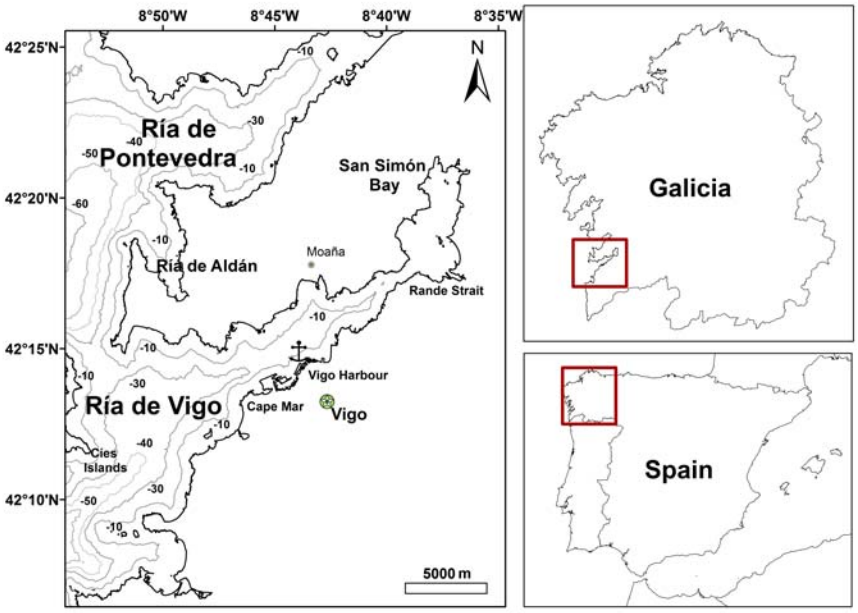

Fig. 1. The study area was located in the Ría de Vigo (NW Spain).

This Ría is characterized by shorter water residence time - between 14 and 7 days for the upwelling season (Álvarez-Salgado *et al*., 2000). The upwelling episodes are related to the northerly winds from March to September and cause a massive phytoplankton productivity (~1.4 $gCm^{-2}d^{-1}$) inside the Rías during the upwelling season (Figueiras *et al*. 2002). The extension and intensity of seasonal upwelling and downwelling favourable periods varies strongly from year to year.

Most parts of Ría de Vigo coast correspond to sheltered or semi-exposed zones. Sand is alternated with rocky substrate covered with a wide diversity of seaweeds. It should be mentioned that only seaweeds that are able to form patches larger than the pixel size are identifiable by remote sensing. Seaweeds that occur as small patches or are located as a basal stratum of larger macroalgae and seagrasses cannot be mapped with remote sensing.

Three main macroalgal Divisions - Chlorophyta, Phaeophyta and Rhodophyta, or green, brown and red macroalgae respectively, are present in the Ría de Vigo. Rocky intertidal areas are dominated by brown macroalgae belts such as *Pelvetia canaliculata*, *Fucus spiralis*, *Fucus vesiculosus*, *Bifurcaria bifurcata* and *Ascophyllum nodosum*. In some places red macroalgae such as *Mastocarpus stellatus*, *Caulacanthus ustulatus*, *Chondracanthus* sp., *Gigartina pistillata* and *Chondrus crispus* form caespitose communities underneath the cover of different intertidal *Fucaceae* but their presence is less common than brown macroalgae. In some pools that appear in low tide it is also common to find some green macroalgae like *Entheromorpha* sp.

The subtidal zone is dominated by large brown macroalgae like *Laminaria saccharina*, *Laminaria ochroleuca*, *Laminaria hyperborea*, *Saccorhiza polyschides*, *Halydris siliquosa*, *Himantalia elongata*, *Cystoseira baccata* and the invasive seaweed *Sargassum muticum* that can cover extensive areas. Red macroalgae are smaller in size and are usually located on the basal substrate of brown macroalgae and it is also less common to find them in larger patches. The most characteristic red macroalgae in the subtidal zone are *Asparagopsis armata*, *Gracilaria multipartita*, *Gracilaria gracilis***,** *Gelidium spinosum* and *Rhodymenia pseudopalmata*. Some red calcareous macroalgae, like *Corallina officinalis,* are also present in the study area. Large belts of *Ulva* sp. and the seagrasses *Zostera marina* and *Zostera noltii* occur in sheltered areas of the medium/lower intertidal and upper subtidal zones. The presence of rather large homogeneous patches of *Codium tomentosum* is also typical in more exposed zones. This description of the study area was based on studies by John (1971), Bárbara and Cremades (1993), Veiga-Villar (1999), Cremades *et al*. (2004), Olabarria *et al*. (2009), Filgueira and Castro (2010), among others, as well as in personal observations.

2.2 Field spectroscopy

A field spectroscopy campaign for characterisation of the water column was carried out from 19th June to 22nd June, 2008. Three spectroradiometers were used to collect irradiance and reflectance data: an ASD FieldSpec FR spectroradiometer with a spectral range from 350 to 2500 nm (sample interval of 1 nm) and two Ocean Optics USB2000 spectroradiometers with a spectral range from 350 to 1100 nm (sample interval of 0.5 nm).

The ASD FieldSpec FR was fixed to the bow of the boat used during the field work, avoiding the possible influence of the boat shadow. Measurements were made during the central daylight hours to keep solar illumination conditions as similar as possible. In this way, the solar irradiance (E_s), radiance of the light reflected from the water (L_{sfc}) and diffuse sky radiance (L_{sky}) were measured following the NASA protocols (Fargion and Mueller, 2000). Duration of the measurements in each point was less than one minute guaranteeing the minimum illumination variations. Measurements were calibrated using a Lambertian surface with 25% reflectance.

Upward (E_u) and downward irradiance (E_d) were measured at different depths using two subaquatic cosine collectors placed in a “T” support, with an orientation of 180˚ from each other, and connected to the Ocean Optics spectroradiometers through two optical fibres. The support was covered with black adhesive tape to eliminate any interference with measurements. Besides, a plumb was placed in the ends of the support to reduce the movement and keeping the measurement as perpendicular as possible with the water surface. Measurements were made with 0.5 m or 1 m intervals depending on the depth.

Moreover, spectral signatures of different macroalgal species were measured. To complete the spectra measured between 19th and 22th of June a second campaign was carried out in August 2009. Macroalgae were recollected and transported to the shore for reflectance measurements. To achieve a pure signal, leaves where piled on a black matt in multiple layers (O’Neill et al., 2011). Measurements were made by an ASD FieldSpec FR spectroradiometer and using a high intensity contact probe which housed a 100 W halogen lamp. This optical system design minimizes measurement errors associated with stray light and shadows. Measurements were calibrated using a 99% Lambertian surface. Reflectance spectra of 8 brown macroalgae species (n=53), 6 red macroalgae species (n=21) and 3 green macroalgae species (n=12) were measured using this method. Spectra of sand (n=8) were also measured (Table 1). These measurements represent the “pure” spectra of each substrate type.

Table 3. Species of seaweeds and number of spectral samples (N) measured during the field campaign with the spectroradiometer ASD FieldSpec FR.

Species	Codes	N
Division Chlorophyta		
Codium tomentosum	*Cod*	3
Enteromorpha sp.	*Ent*	3
Ulva sp.	*Ulv*	6
Division Phaeophyta		
Ascophyllum nodosum	*Asc*	3
Bifurcaria bifurcata	*Bif*	6
Cystoseira baccata	*Cysb*	16
Fucus vesiculosus	*Fv*	3
Himanthalia elongata	*Him*	2
Laminaria saccharina	*Lam*	10
Sacchoriza polyschides	*Sacc*	2
Sargassum muticum	*Sar*	11
Division Rhodophyta		
Asparagopsis armata	*Asp*	3
Ceramium rubrum	*Cer*	2
Chondrus crispus	*Chon*	6
Gigartina piscillata	*Gpis*	3
Gigartina tedii	*Gte*	4
Coralina officinalis	*Coffi*	3

Some other species of seaweeds, different from the ones indicated in the Table 1, such as *Laminaria ochroleuca*, *Laminaria hyperborea*, *Chorda phylum*, *Halidrys siliquosa*, etc could form large enough patches to be detected by remote sensing sensors. However we were not able to find and measure them during the fieldwork campaign.

2.3 CASI (Compact Airborne Spectrographic Image) sensor

The hyperespectral sensor CASI-2 was chosen to assess the possibility of macroalgae mapping on the Ría de Vigo coast. The choice of this sensor was made taking into account its high spectral and spatial resolution. These characteristics are considered an advantage in such heterogeneous environments like coastal zones. For this reason, the CASI sensor has been used for benthic mapping in shallow waters worldwide (e.g. Bertels et al., 2008; Hunter et al., 2010; Larsen et al., 2011; Leiper et al., 2012).

The CASI sensor is a push-broom imager capable of flexible image collection in visible and near-infrared wavelength regions. The user can modify the number and position of the spectral bands according to the specific requirements of each study. Making use of this technical possibility and taking into account the peaks and shoulders in macroalgae reflectance spectra (e.g. Maritorena et al., 1994; Hoechberg and Atkinson, 2000; Vahtmäe et al., 2006) a configuration of 25 bands from 399 to 1045 nm was chosen. Most of the spectral bands were around 5 nm wide except the first and the last band which were around 20 nm (Table 2). This configuration has already been used with success by Kutser et al. (2011) in shallow water benthic mapping in the coastal waters of the Baltic Sea. The spatial resolution of the CASI sensor is a function of the altitude at which the instrument is flown. For example, if it is flown at around 900 m altitude then the spatial resolution is 1 m. The 1 m spatial resolution would be useful as coastal habitats are quite heterogeneous.

Table 4. Bandset configuration of CASI-2 figured for this study.

Band	Centre (nm)	Band	Centre (nm)
1	370.0	14	649.3
2	398.6	15	673.1
3	439.2	16	699.4
4	458.3	17	718.5
5	479.8	18	739.9
6	498.9	19	759.0
7	520.3	20	779.3
8	549.0	21	818.7
9	568.1	22	837.8
10	589.6	23	879.5
11	601.5	24	939.1
12	620.6	25	1045.2
13	629.0		

Another relevant aspect to assess a sensor is the signal to noise ratio (SNR). The SNR specifications currently attainable by airborne remote sensing systems like CASI, flown under ideal circumstances, are about 1000:1 (Dekker et al., 2001). About 48% of the just below the water surface upwelling irradiance is reflected back into the water column (Vahtmäe et al., 2006). Thus, the SNR in terms of just below the water surface reflectance, $R(0^-)$, has to be 500:1 to be able to detect differences in reflectance spectra by the abovementioned instruments (Dekker et al.2001; Vahtmäe et al., 2006). It is also necessary to take into account that airborne imagery is affected by other sources of noise such as environmental noise or image noise. However, this issue would have to be assessed in each specific study. In this study we assume ideal conditions. Following Vahtmäe et al. (2006) for simplicity of equations, we assumed that two substrates can be differentiated each other by the CASI sensor if their spectral difference is higher than 0.2% which is equal to SNR 500:1 in terms of underwater reflectance. On the other hand for emerged substrates we consider that two substrates are differentiable from each other if their spectral difference is higher than 0.1%.

2.4 Data analyses

2.4.1 Statistical analyses

Statistical analyses were carried out to study the spectral differences at species level as potentially detected by the CASI sensor. In order to identify marine vegetation by means of remote sensing the vegetation types have to be spectrally separable (Skidmore et al., 1988) meaning that the variance of the reflectance must be greater between species than within species (Schmidt and Skidmore, 2003).

Multivariate techniques were used to compare the intra- and inter-species variability as well as their spectral proximity. An association matrix was generated for macroalgae spectra using the Bray-Curtis similarity index. Subsequently, this similarity matrix was used in non metric multidimensional scaling (nMDS) and in the analysis of similarity test (ANOSIM). Both methods were also used by Fyfe (2003) to assess the separability of three seagrass species. On the one hand, nMDS was used to produce two-dimensional ordination plots to provide a visual representation of the pattern of proximities (i.e., similarities or distances) among a set of objects, in this case macroalgal species. nMDS seeks to minimize "stress", which is the departure of the distances between samples in the original similarity matrix (Clarke 1993). On the other hand, in this study ANOSIM was used to compare ranks of between–species to within-species similarities using a randomization test of significance in order to test the null hypothesis that species do no differ (Clarke and Warwick, 1994; Legendre and Anderson, 1999). ANOSIM constructs a test statistic (R) based on the difference of mean ranks between and within species. A value close to 0 indicates little or no separation whereas a value close to 1 indicates complete separation between species (Clarke, 1993). R values>0.75 are interpreted as indicating strong separation, R>0.5 as separation with overlap and R<0.25 as barely separable (Clarke and Gorley, 2001). This analysis also provides information about within and between species variability.

However, these tests do not give information about the specific spectral bands where the main differences occur or what species are differentiable from each other. Regarding this issue univariate analysis were carried out. For this analysis the data at each wavelength was assessed for normality using Shapiro-Wilks test and Q-Q plots. Although it is reasonable to assume a normal distribution of the spectral response for any homogenous target material (Lillesand and Kiefer, 1994), most of wavelengths did not show a normal distribution. The data at each wavelength was also examined for homocedasticity using Cochran's test (Winer, 1971). The Cohran's test results showed that most of the variances were heterogeneous. For this reason a Kruskal-Wallis test was used to analyse the existence of significant differences between macroalgae species at each wavelength band and its post-hoc allows establishing which macroalgae pair is significantly different at each wavelength band. The Kruskal-Wallis test is a non-parametric method which does not assume a normal distribution of the sample sets (in this case, the reflectance measurements per waveband) or homogeneity of variances (homocedasticity). For significant differences in Kruskal-Wallis test multiple comparisons were made using its post-hoc version. Uni- and multivariate statistical analyses were performed using the R software for the spectra resampled to CASI-2 bands.

2.4.2 Bio-Optical Modelling

The water column effect was evaluated for CASI-2 bands by simulating bottom-reflected light through water with different depths. Taking into account that only a low number of species showed significant differences between them and that these differences seldom appeared within a group (green, brown or red) (see section 3.1) the bio-optical modelling was carried out at group level. Since spectra within a group are consistent in shape, the spectra of *Ulva* sp. was chosen as representative of the Chlorophyta, *Fucus vesiculosus* of the Phaeophyta and *Chondrus crispus* of the Rhodophyta. It is necessary to consider also sand and deep water spectra if we are discussing the potential for distinguishing macroalgae from their surroundings. For this reason both were included in this analysis.

In this study a simple model developed by Maritorena *et al*. (1994) for shallow waters was used to establish the water column influence on the shallow water reflectance spectra. The model was developed for reflectance just beneath the water surface as:

$$R\ (0^{-}, z) = R_{\infty} + (R_b - R_{\infty})^{*} \exp\ (-2Kz)$$

where z corresponds to bottom depth (m), R_b to the bottom reflectance and R_{∞} with reflectance of optically deep water just beneath the sea surface. As water depth was measured from the boat above the water column the air-water boundary needs to be taken into account. The presence of this boundary has a significant effect both on the magnitude of energy entering the water column and the radiance signal exiting the water surface. A factor of 0.54 (Austin, 1974) was applied to the deep water spectrum to compensate there fraction at the air-water boundary. The operational attenuation coefficient, *K*, represents attenuation of the downwelling stream, and the upwelling stream originating both from the bottom and from the water column (Maritorena *et al*. 1994). Following these authors we have considered the vertical diffuse attenuation coefficient (K_d) as a good approximation for *K*.

The bio-optical model simulations were carried out for green, red and brown macroalgae species as well as sand. By simulating bottom-reflected light, the effects of water column on the CASI-2 sensor spectra were evaluated at different depths. The spectral differences between benthic substrates, as well as deep water and sand were calculated by subtracting the reflectance of one substrate from the reflectance of another substrate at the same depth following Kutser et al. (2003) and Vahtmäe *et al*. (2006). The minimum difference value at which two substrates can be differenced was established taking into account the SNR of CASI sensor, 0.2% of reflectance for submerged substrates and 0.1% for emerged substrates. It was assumed that each measurement by a sensor was of a “pure” substrate type (i.e. no mixes).

Bio-optical modelling results were validated comparing the resulting spectra with those measured in field of known bottom and depth. Comparisons were carried out for 5 sampling points. It is necessary to consider that the comparison is not direct because the measurements were carried out from the bow of the boat and that the air-water boundary needs to be taken into account. The error between both spectra was assessed using the root mean squared (RMS).

3.RESULTS

3.1. Statistical analyses

The results of the ANOSIM test for the species within the red (R global=0.312, $p \leq 0.002$), green (R global=0.547, $p \leq 0.002$) and brown macroalgae groups (R global=0.615, $p \leq 0.001$) showed significant separation between species (Fig.2). However, the relatively low R global values indicate overlapping. The graphic representation of ANOSIM for macroalgae variability within each group showed in most of the cases high intra-species variability. However, the inter-species variability was higher in the three analysed groups.

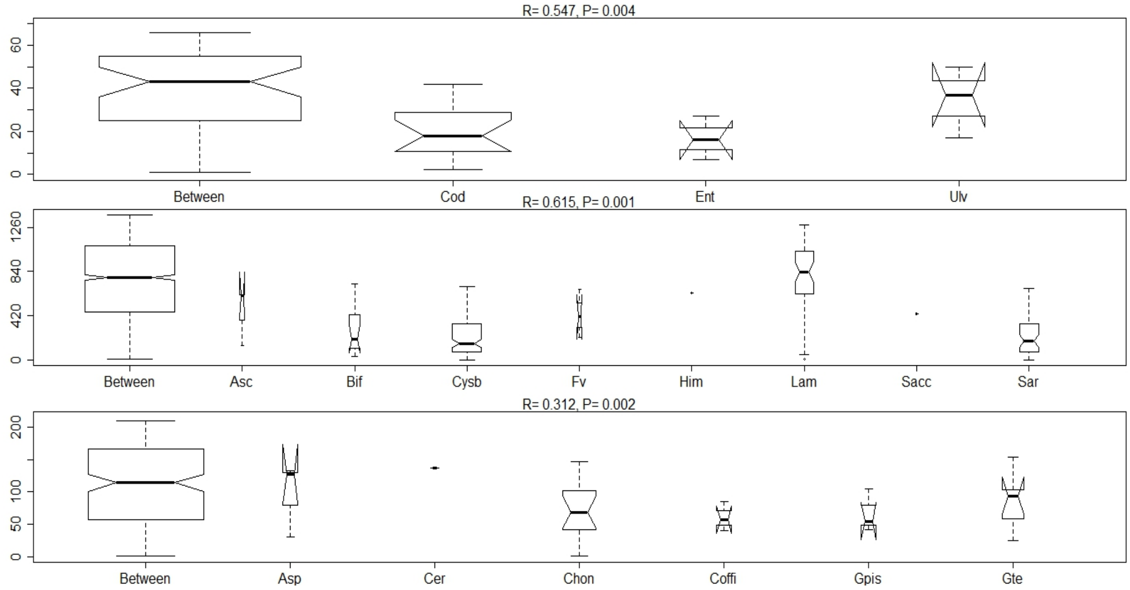

Fig. 2. Comparison of within species variability with between species variability in the three macroalgal groups. From up to down: green macroalgae group, brown macroalgae group and red macroalgae group. For each group of observations, the box limits represent the lower quartile (25-th percentile) and upper quartile (75-th percentile). The median is displayed as a line across the box. The notch marks the 95% confidence interval for the medians. The dashed lines represent whiskers and extend to the largest observation that is less than or equal to the upper quartile plus 1.5 times the interquartile range (or the smallest observation that is greater than or equal to the lower quartile minus 1.5 times the interquartile range).

These results are confirmed by nMDS analysis. The nMDS plot representation (Fig.3) for all macroalgal species showed that differentiation between species seems not to be related to their taxonomy. Analysing visually the plot, it can be distinguished some small groups. *L. saccharina* is the species most distant to the other. A well-defined group would be the one formed by *C. tomentosum*, *C.rumbrum* and *S. polyschides*. The rest of the groups represented in the plot are less defined and some species appear situated very close each other as occur with *C. baccata* and *G. tedii* and with *B. bifurcata* and *A. armata*. Moreover, *C. officinalis* seems to be separable from the previous groups though this differentiation is not as clear as in the case of *L. saccharina*.

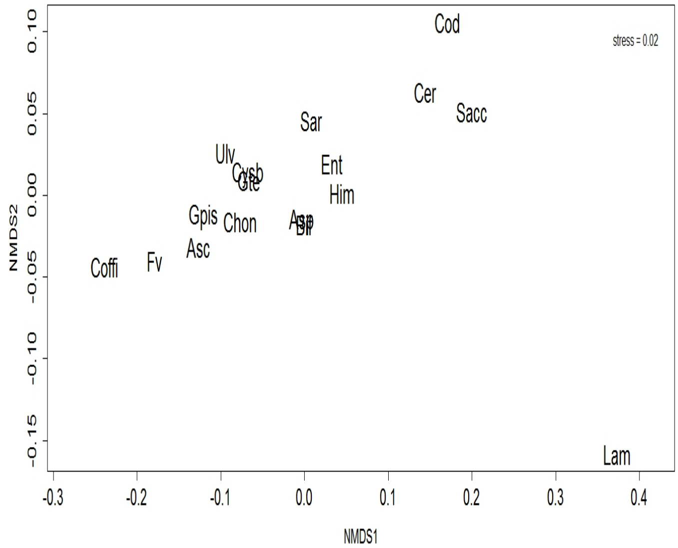

Fig. 3. Non-metric multidimensional scaling (nMDS) ordination plot for macroalgae species. The nMDS was calculated for each species mean. Stress level represents the ability of the ordination to accurately capture the multidimensional similarity matrix in two dimensions. A stress of 0.02 indicates an excellent representation (See Table 1 for codes of species).

The Kruskal-Wallis tests for all wavelengths showed significant differences for all macroalgae groups ($p<0.05$). The results of Krukal-Wallis post-hoc tests showed the pairs of species where significant differences were found (Table 3). In general differences appeared between species belonging to different groups. The greatest number of significant differences between all macroalgae pairs studied was gathered at infrared wavelengths from 740 to 1045 nm. However, these differences could be only detected when macroalgae are emerged due to the very strong light absorption by water at these wavelengths. Regarding the visible region of electromagnetic spectrum, the wavelengths where a higher number of significant differences were located corresponds with 480, 568, 599 and 601 nm bands. The pairs of macroalgae species that showed differences in the most number of the wavelengths, and in consequence the most differentiable, were *C. tomentosum* - *C. officinalis* and *C.* officinalis-*L. saccharina.*

Table 5.Pair-wise comparisons of spectra at species level using Kruskal-Wallis post-hoc test (p<0.05 is represented by a x). Species that did not show significant differences were not included in the Table. See Table 1 for codes of species

	Wavelength (nm)																								
Species pair	370	399	439	458	480	499	520	549	568	599	601	621	629	649	673	699	718	740	759	779	819	838	879	939	1045
Asc-Cod			x	x	x	x		x	x	x	x														
Asc-Lam																		x	x	x	x	x	x	x	x
Bif-Cod								x	x	x	x	x	x	x											
Bif-Gte									x																
Chon-Cod	x				x		x			x	x	x	x	x											
Chon-Lam																	x	x	x	x	x	x	x	x	
Cod-Coffi	x	x	x	x	x	x	x			x	x	x	x	x	x					x	x	x	x	x	x
Cod-Cysb																					x	x	x	x	x
Cod-Fv									x	x	x										x	x	x	x	
Cod-Gpis														x											
Cod-Lam		x	x	x	x	x																			
Coffi-Ent														x											
Coffi-Lam																x	x	x	x	x	x	x	x	x	x
Cysb-Lam																	x	x	x	x	x	x	x	x	x
Fv-Lam																	x	x	x	x	x	x	x	x	x
Gpis-Lam																	x	x	x	x	x	x	x		
Gte-Lam																	x	x	x	x					
Lam-Sar																								x	x

2. Bio-optical modelling

Prior to the bio-optical modelling the differences between each macroalgae group as well as with sand and deep water were analysed without water column influence. The spectral differences between benthic substrates, as well as deep water were calculated by subtracting the reflectance of one substrate from the reflectance of another substrate.

Green macroalgae (*Ulva* sp.) showed a broad peak centred at 549 nm. Regarding brown macroalgae (*F. vesiculosus*) a main broad peak also appeared at 568, 599 and 601 nm. Subsequently, in the following wavelengths the reflectance values decrease but a secondary peak can be detected at 649 nm. Red macroalgae (*Ch. crispus*) showed a first peak at 520 nm followed by a prominent shoulder at 568 nm. A second remarkable peak appears with maximum values at 599 and 601 nm while in the following wavelengths reflectance values decrease slightly appearing a secondary peak at 649 nm. All mean reflectance values showed a well-marked shoulder at 673 nm (Fig4.A).

Regarding the macroalgae groups differences (Fig.4B), it was observed that *Ulva* sp. and *F. vesiculosus* are differentiable at all wavelengths with the exception of 370 and 673 nm being located the highest differences at 599 and 601 nm. Regarding *Ulva* sp. and *Ch. crispus* all wavelengths showed higher values than SNR. The main differences were located at 599, 601, 649 nm and 718 nm. *F. vesiculosus* and *Ch. crispus* comparison showed values higher than CASI SNR in all wavelengths with the exception of 439 nm. The highest differences were found at 370, 520, 568 and 649 nm. When it comes to brown and red macroalgae, difference values decrease slightly. In the three cases the differences were higher at infrared wavelengths. Concerning sand and macroalgae, difference values were high, especially at visible wavelengths due to the absence of chlorophyll in sand substrate (Fig.4C). All macroalgae were differentiable from deep water showing larger differences at wavelengths upper than 673 nm (Fig.4D).

Bio-optical modelling results showed that the maximum depth at which green macroalgae can be differentiated from deep water was 6 m (Fig. 5A). Results showed that brown algae can be differentiated until the same depth using the bands at 549 and 568 nm. On the other hand, the results showed that red macroalgae and deep water could be differentiable until 5 m at 520, 549 and 568 nm (Fig. 5B). Differences between macroalgae and deep water were larger in the infrared part of the spectrum (from 699 to 740 nm) however deeper than 2 m these differences were drastically reduced because of the strong absorption of light by water (Fig. 5C). Sandy bottoms showed higher differences compared to deep water and sand can be differentiated from deep water until 13 m depth (Fig. 5D).

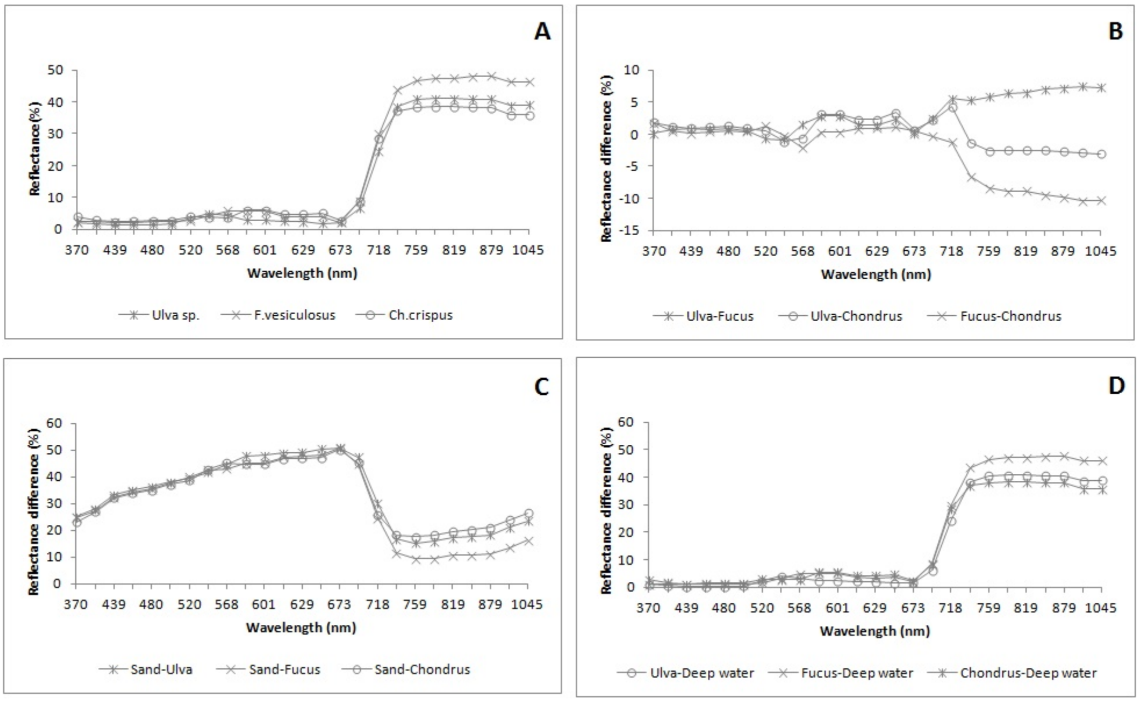

Fig. 4. A) Mean reflectance values of Ulva sp., F. vesiculosus and Ch. crispus. Only wavelengths until 699 nm were represented here due to the dominance of infrared values that masked the differences in the visible region. B) Reflectance differences between the three macroalgal groups. C) Reflectance differences between sand and the three macroalgae groups. D) Reflectance differences between deep water and the macroalgae groups.

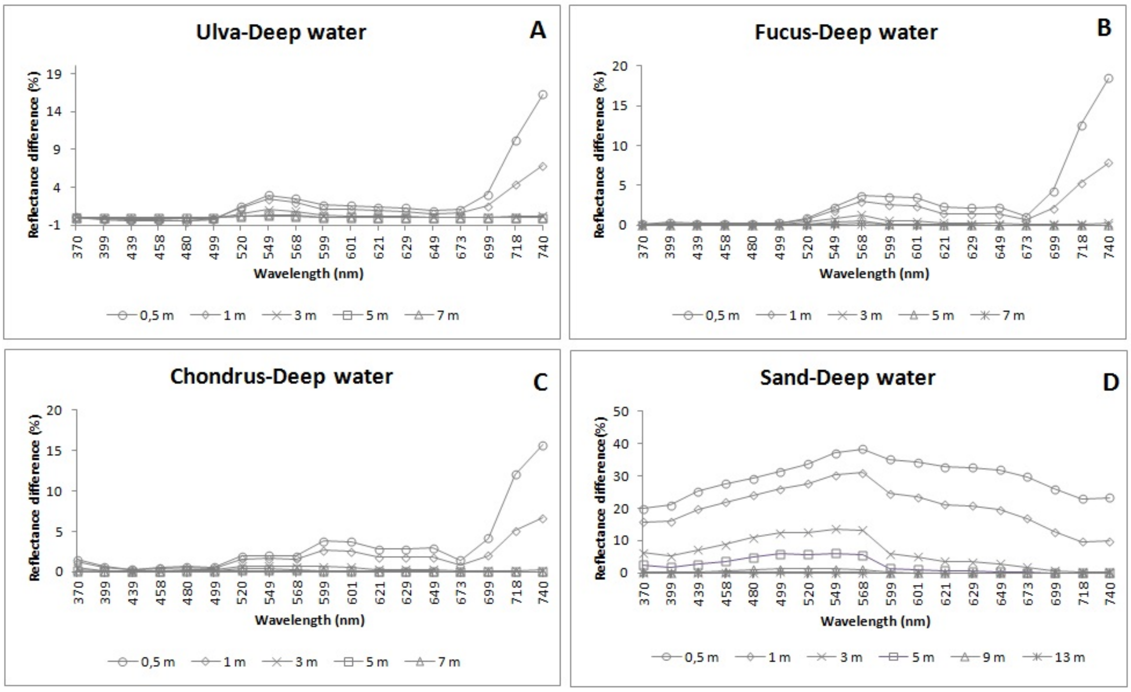

Fig. 5. Spectral differences between simulated reflectance spectra for sand and each macroalgae group respect to deep water at several water depths.

Regarding the spectral differences between macroalgae groups when they are submerged, *Ulva* sp. showed higher reflectance values than *F. vesiculosus* in all wavelengths with the exception of 520 and 549 nm. These differences were largest in the range from 568 to 649 nm and from 669 to 740 nm. Differences in the infrared part (669 to 740 nm) decreased with depth more drastically than differences in visible part (568 to 649 nm). Simulation showed that the maximum depth at which those species can be separated using a hyperspectral sensor like CASI-2 is 4 m (Fig.6A). *Ulva sp.* showed higher reflectance values than *Ch. crispus* with the exception of 549 and 568 nm. Simulation showed that the maximum depth at which these species can be separated is also 4 m (Fig.6B). The range of differences values is lower than previous comparisons with green algae (*Ulva* sp.) because brown and red algae are relatively darker. *F. vesiculosus* showed higher values than *Ch. cripus* at 549 and 568 nm as well as upper than 699 nm. These differences are also detectable until 4 m depth (Fig.6C). All macroalgae groups showed high differences respect to sand. Simulation results showed that these differences can be detected using CASI-2 sensor until 10 m using the 480, 499, 520, 549 and 568 nm bands (Fig. 6D-F)

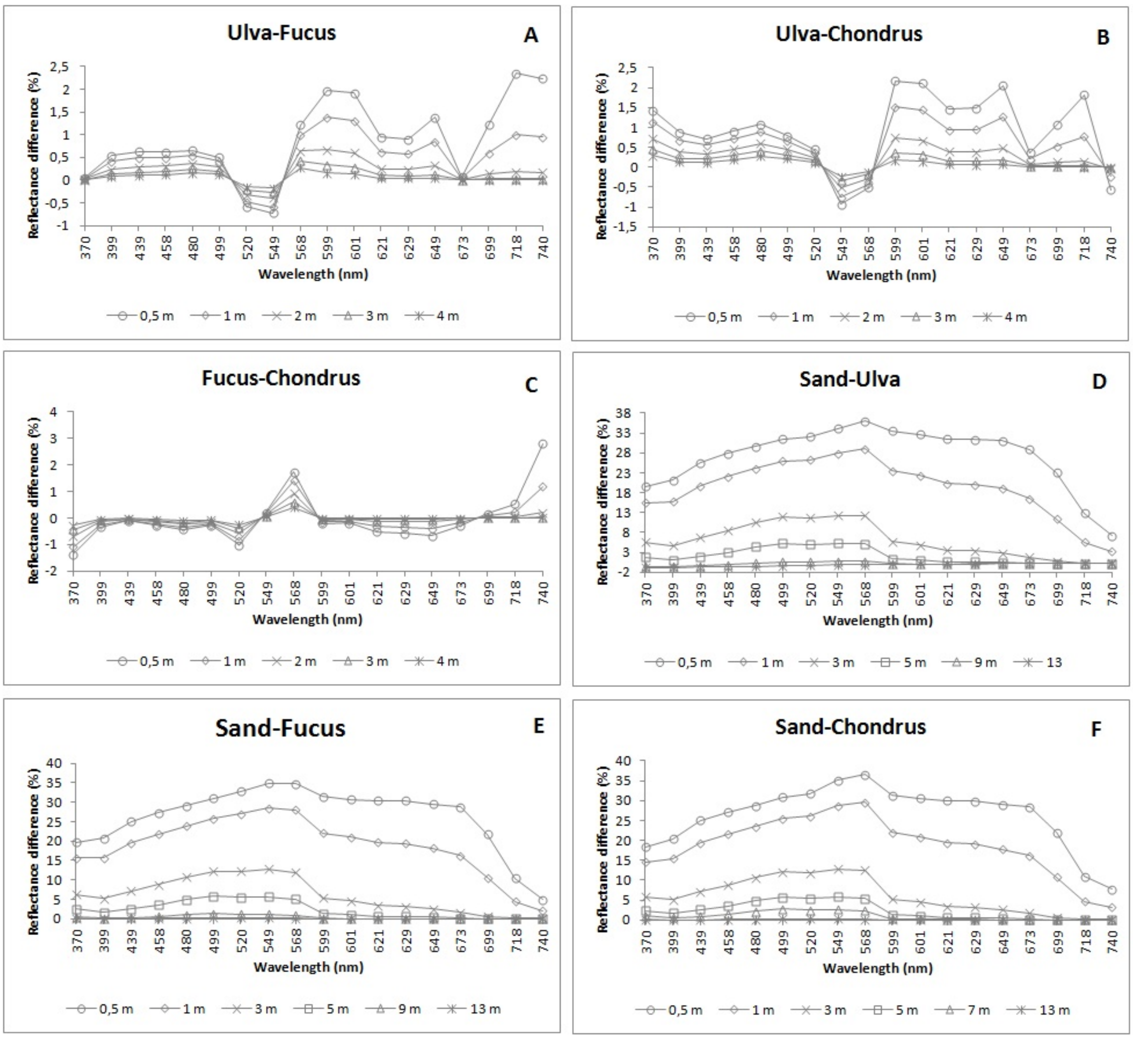

Fig. 6. Reflectance differences of simulated spectra at several depths between green (Ulva sp.), brown (F. vesiculosus) and red (Ch.crispus) macroalgae as well as sand.

The validations of bio-optical model results showed a RMS average of 0.017 indicating that calculations for R (0-,z) were successful (Fig. 7).

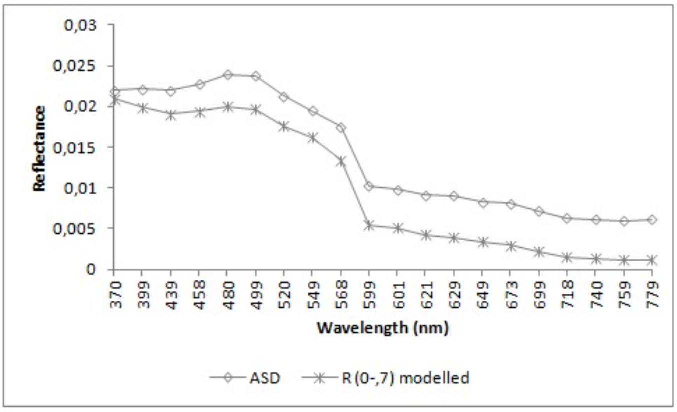

Fig. 11. Comparison between the above water measurements carried out with a ASD FieldSpec spectroradiometer and the $R(0^-,z)$ modeled using the bio-optical model. Both spectra correspond with measurements carried out at 7 m depth over macroalgae substrate. The RMS for this point was 0.012.

4.DISCUSSION

In the last decades, remote sensing has been proved to be a powerful technology for monitoring the earth's surface at a global, regional, and even local scale. In this sense multiple applications have been referenced using this type of techniques in different fields. However, mapping of shallow benthic habitats continues to be a challenge to solve despite of the new hyperspectral sensors with high spectral and spatial resolution.

Water strongly absorbs the electromagnetic radiation, resulting in significant dampening of the radiometric signal (Silva et al., 2008). Because of this, reflectance spectra of submerged vegetation are usually very low, on the order or 10^{-1} (Dierssen et al., 2003; Fyfe 2003) especially in the near to mid-infrared regions where the absorption by water molecules is stronger. Also the main differences between different vegetation types are in the green to near infrared part of the spectrum. For this reason the main challenge of remote sensing of submerged aquatic plants is to isolate the plant signal from the overall water column interference (Silva et al., 2008). This issue gains special importance in the coastal waters, where most of submerged vegetation appears. In this region, spectral scattering and absorption by phytoplankton, suspended organic and inorganic matter, as well as, dissolved organic substances also restrict the light passing to, and reflected from the benthos (Dekker et al., 2001). For this reason, when it comes to apply remote sensing to map benthic communities, it is fundamental to take into account the limitations, such as wavelength-specific penetration of light trough the water, substrates spectral differences, etc. to avoid false expectations. Therefore, it is reasonable to use bio-optical or radiative transfer models prior to the image collection in order to estimate how much and where can be achieved with remote sensing. For this reason many authors such as Maritorena et al. (1994), Kutser et al.(2003), Purkis et al. (2004) ,Vahtmäe et al., (2006) or Mao et al. (2010) bet for the use of this method in their studies.

The success of a remotely sensed image classification, from CASI or other sensor, depends on the separability of spectra reflected from different types of habitat in the imagery (Mumby et al., 1997). In the present study the visual analyses showed that the spectra within a species and even within a same group (green, brown and red) were consistent in shape but variable in reflectance values as was seen by Hedley and Mumby (2002) or Kutser el al., (2006b). Statistical analyses at species level showed that macroalgae species, resampled to CASI-2 wavelength bands, were very similar each other. ANOSIM analyses showed a high intra-specific spectral variation as was pointed out by Hedley and Mumby (2002). Moreover, the ANOSIM analyses carried out in this study did not show a clear separation between macroalgae species within a group (global $R=0.547$, $p\leq0.004$ for green, global $R=0.615$, $p\leq0.001$ for brown and global $R=0.312$, $p\leq0.002$ for red macroalgae) as on the contrary was reported by Fyfe (2003) for the three seagrass species (global $R=0.926$, $p\leq0.001$). This can be explained because the three seagrass species analysed by Fyfe (2003) showed similar values at visible wavelengths. However, their reflectance values did not overlap each other at infrared wavelengths. This could indicate that the possible differentiation found by Fyfe (2003) lie in the leaf structure and not in pigment composition. However, these differences at infrared wavelengths could not be detected if seagrass were submerged.

On the other hand, nMDS showed that the species more distant were *L. saccharina*, *C. tomentosum* and *C. officinalis*. In some cases species of different groups are closer than species belonging to the same group. This could be explained by the high intra-species variability that provokes the overlapping of spectra of different species. Univariate analyses supported these results showing significant differences only for a small group of macroalgal species. Most of the species that showed significant differences in the univariate analyses present important differences at infrared wavelengths. For example, *L. saccharina* and *C. tomentosum* present low values at these wavelengths with regard to other species whereas *C. officinalis* presents high values due to its calcareous structure. This indicates that the differences detected by ANOSIM and nMDS were mainly due to differences at infrared wavelengths. This was also confirmed by univariate analysis showing that differences between species of different groups were mainly significant in the visible part of the spectrum (from 370 to 649 nm) while differences between species belonging to the same group were significant mainly at infrared wavelengths (from 718 to 1045 nm).

The difficulties in spectral separability at species level have been reported also by other authors even in the case of terrestrial vegetation (Anderson, 1970; Price, 1992; Kutser et al., 2006b; Sobhan, 2007). Spectral differences at the species level are difficult to solve because they are described by a small number of independent variables (Price, 1992). The reflectance response of vegetation in visible wavelengths is primarily determined by the composition and concentration of pigments such as chlorophyll-a, chlorophyll-b and the carotenoids (Tucker and Garrett, 1977; Richardson et al., 2002) and there is a very little difference in the spectral response in this spectral region at the species level (Anderson, 1970). Conversely, leaf morphology and water content are the main factors acting on the infrared wavelengths (Knipling, 1970; Danson, 1995; Silva et al. 2008). The reflectance of vegetation from different species is highly correlated due to their common chemical composition (Portigal et al., 1997). Statistical analyses can be an approximation for the assessment of sensor performance but more realistic results are obtained when peaks and shoulders positions are taken into account (Hedley and Mumby, 2002; Kutser et al., 2006b). Spectral shapes are consistent in the visible part of the spectrum within macroalgal groups due to the presence of characteristic pigments. Differences in the infrared part of the spectrum could give more information about differentiation at the species level; however these wavelengths are lost when substrates are submerged.

This issue justify that the analyses of differences in emerged macroalgae as well as the bio-optical model were carried out at the group level. Chlorophyta, Phaeophyta and Rhodophyta have distinctive complementary pigments which define the groups and result in a basic spectral dissimilarity between them (Daves, 1998). In fact, the evolutionary division of these groups is based on pigment composition, and reflectance spectra are similar for many of these species because of their similar pigmentations (Beach et al., 1997). However, the relative concentrations of photosynthetic and accessory pigments will also vary within a plant species because of genetic variation, seasonal cycles, state of growth, health or environmental conditions (Dawson and Dennison, 1996; Alcoverro et al., 2001).

Reflectance spectra used in this study for green (*Ulva* sp.), brown (*F. vesiculosus*) and red macroalgae (*Ch. crispus*) were consistent in shape with other studies (Maritorena et al. 1994; Kutser et al., 2006b; Vahatmäe et al., 2006; Thorhaug et al., 2007) indicating that spectral features typical of the macroalgae analysed in this study are the same as in other water bodies. Reflectance values were lower at visible wavelengths due to the chlorophyll absorption whereas these values increase considerably at infrared wavelengths. In all spectra a well-defined shoulder at 673 nm appears due to the chlorophyll-a absorption present in all macroalgae. On the other hand, all macroalgal spectra resampled to CASI-2 bands showed the typical peaks and shoulders of each macroalgae group. However, in some cases they were slightly shifted due to the presence of specific bands. *Ulva* sp. showed a broad peak centred at 549 nm. This peak can be explained by chlorophyll-b absorption (480 nm) and β-carotene absorption (427, 449 and 475 nm) that provoke low values in the bands from 370 to 499 nm. The shoulder of chlorophyll-b absorption at 650 nm it is also detectable at 649 nm. On the other hand, *F. vesiculosus* showed a broad peak at 568, 599 and 601 nm. Absorption of chlorophyll-c (460 and 633 nm) and the typical brown algae pigment xantophyll fucoxanthin (426, 449 and 465 nm), were evident in the low values from 370 to 520 nm. A small shoulder appears at 629 nm due to chlorophyll-c absorption. However the absence of 633 nm band may have caused that this peak does not appear well-defined. In red macroalgae spectra there is a well marked shoulder at 568 nm that corresponds to phycoerythrin, pigment characteristic of red macroalgae, absorption. A secondary shoulder due to this pigment was also noticed at 549 nm. The real absorption of phycoerithrin would be 543 nm however the absence of a CASI-2 band at this wavelength shifted this absorption peak to 549 nm. The presence of chlorophyll-c was also detectable by a small shoulder at 629 nm. From 370 to 499 nm low reflectance values appeared due to β-carotene and α-carotene absorption. The absorption of phycocyanins (553 and 618 nm) and allophycocyanins (around 654 nm) were not represented in the red macroalgae spectra due to the absence of these wavelengths in the CASI-2 configuration besides the high concentration of phycoerithrin can mask the presence of these pigments.

The bio-optical modelling carried out in this study shows that using CASI-2 sensor deep water could be separated from green and brown macroalgae until 6 m and from red macroalgae until 5 m. Whereas and deep water could be differentiated until 13 m. Moreover, differences between macroalgae and sand were detectable using the CASI-2 sensor until 10 m because sand substrate is very bright in comparison with macroalgae substrates. However, this model was performed for certain conditions of Ría de Vigo and for a specific sensor. The environmental conditions of water column in the Ría de Vigo can change between seasons as well as the composition of macroalgae assemblages and their pigmentation. For this reason, the results of this study could only be extrapolated to places with similar conditions and for the use of sensors with the same technical characteristics such as SNR, spectral and spatial resolution.

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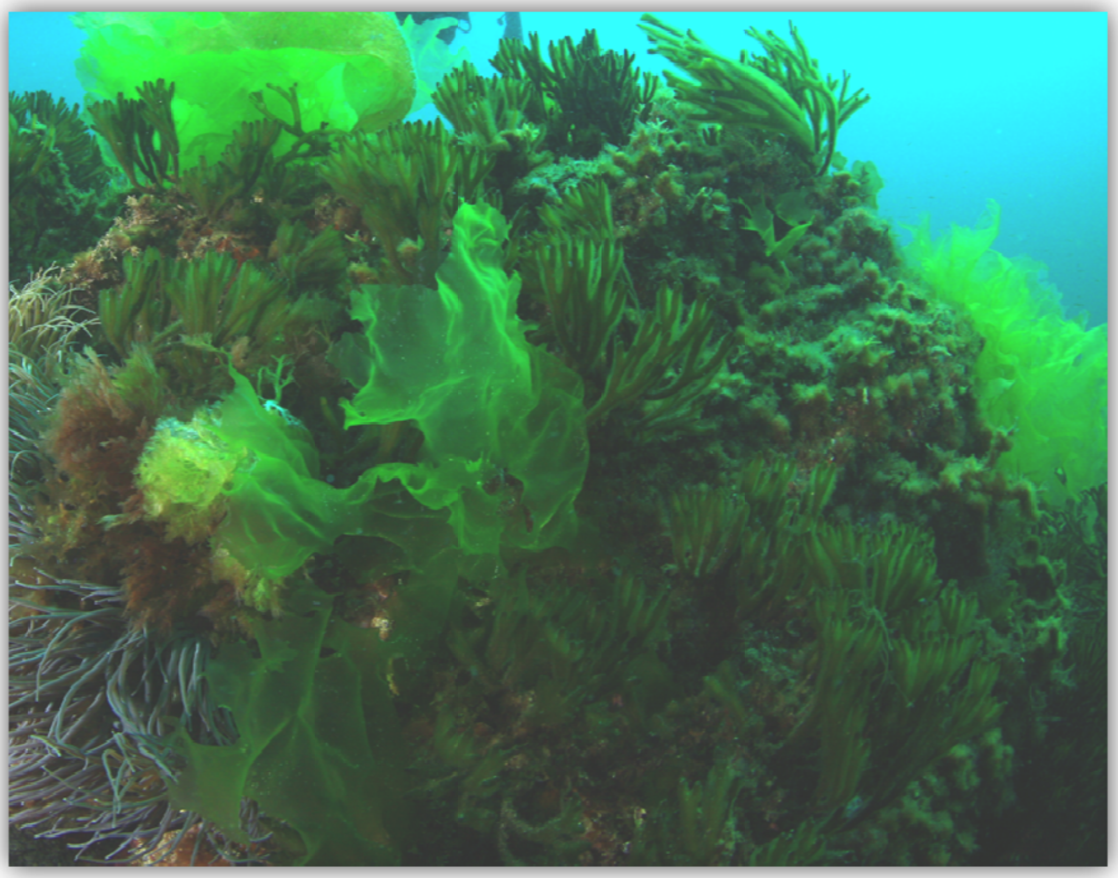

GENERAL DISCUSSION

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The knowledge of the spatial distribution, quality and quantity of seabed resources is fundamental to the understanding of marine ecosystems and to manage human activities for sustainable development and maintain marine ecosystem function (MESH, 2008).

Detailed thematic maps of benthic habitats are important in facilitating conservation of these landscapes, increasing the understanding of factors that can provoke environmental changes. These maps provide georeferenced information on biological cover types in the marine environment and are more useful for management and spatial planning purposes when they are created at a suitable scale (Wedding et al., 2011). Benthic maps are widely acknowledged as a critical step for effective and informed management of marine resources (Kostylev et al., 2001). In the absence of detailed seabed information, decision makers often fell handicapped in making decisions about the effects of different activities on marine habitats (Pandian et al., 2009). In spite of many studies have been carried out regarding spatial distribution of seaweeds, it can result eye-catching that the Nature Editorial (2008) states the absence or inaccuracy of geographical seaweed information. This issue was also reported by Pauly and De Clerck (2010) who demonstrated a remarkable lack of spatial data in seaweed studies to date.

Remote sensing integrated with other relevant geospatial technologies, such as Geographic Information Systems (GIS) offers an indispensable framework of monitoring, synthesis and modelling for coastal environment (Yang, 2009) including the macroalgal assemblages. Both techniques are well-complemented, while remote sensing constitutes an information source that can describe and monitor a variety of systems on a local or global scale, GIS can be used as a spatial analysis tool providing a platform for data integration, synthesis and modelling to support decision making. Moreover, remote sensing and GIS contribute in a great extent to the generation of digital geospatial data.

The application of remote sensing techniques to map shallow benthic habitats has been recognised worldwide. At the beginning these techniques were mainly used for clear waters especially using multispectral sensors (e.g. Lyzenga, 1981; Belsher et al., 1988; Augenstein et al., 1991; Mumby and Harborne, 1999). Clear waters present low concentration of suspended material that makes easy the application of remote sensing. However, due to its potential use and the high technological development, in the last years new more sophisticated sensors have appeared and the application of these techniques has been also spread to optically complex waters (e.g. Vahtmäe et al., 2006; Hunter et al., 2010; Pauly et al. 2011).

As mentioned before, GIS and RS have a potential use in the generation of digital geographic information. However, at the beginning of this thesis the lack of information in Galicia related to this field was remarkable. Only little information was available for users and in most of the cases it was too coarse or the administrative process for data acquisition too arduous. These limitations regarding the bad organisation and the restrictive data policy has been recently recognised by the government (Borobio-Sanchiz, 2011). For this reason, this thesis was originally designed as a contribution for the generation of digital geographic data for the littoral zone, where this scarcity was more significant.

In this way, the first chapter was dedicated to the digitalization of a shoreline for the Galician coast. The location of the shoreline and its changing position through time are of key importance to coastal scientists, engineers and managers (National Research Council, 1990; Douglas and Crowell, 2000). As it was reported by Boak and Turner (2005) both coastal management and engineering design require information about where the shoreline is, where it has been in the past, and where it is predicted to be in the future. On the other hand, scientists that develop their work in the coastal zone need to establish a demarcation for their study area. Thus, in this chapter a shoreline with a scale of 1:750 was digitalized. This shoreline allowed the generation of derivate digitized information such as marsh zones, estuaries, islands and the dynamic segmentation in coastal typologies regarding the type of substrate. Along with this geographical information a detailed criteria library was created. This library includes the criteria that were followed during the digitization in each type of substrate: artificial structures, rocky coast and cliffs, sandy coast and beaches, marshes and islands. Moreover, a sixth group was added including the followed criteria for particular cases that cannot be included in the previously mentioned. Therefore, the process could be repeated and the origin of the generated information can be known. All this information was published on the internet[39]and it was shared under a Creative Commons license.

Nowadays, Galician Government is aware of the importance of geographical information systems and is currently making efforts to generate a standardized geographical database where users can access to the data (Borobio-Sanchiz, 2011). In that sense, the Spatial Data Infrastructure of Galicia (IDEG) (Directive 2007/2/EC of 14 March 2007) was created, which follows the established infrastructure for spatial information in the European Community (INSPIRE). The IDEG gathers, organizes and deals with integrated data, metadata and services related to Galicia that could be located geographically. One of the most remarkable objectives of the IDEG is to open the data to all public authorities, private sector and the general public by providing information, services and standard geographic metadata, and also giving them the possibility to integrate their information into a common IDE. The link http://sitga.xunta.es/sitganet/ allows the users to identify, locate, select and access to a wide variety of resources. In this website, cartographic products related to Galician territory such as hydrography, land cover, limits, population and more can be found. However, this information can be downloaded as sample whereas the complete product has an additional charge and cannot be downloaded directly from this website. On the other hand, the cartographic products related to littoral zone continue being scarce and appear as derived from others sources and not generated specifically for this zone.

Regarding the geographical information about the littoral zone, the recent approval of the Coast Management Plan[40] (2010) need to be mentioned. This plan has generated geographical data that include information about landscape, environment, infrastructures, occupation and land uses, urbanization and legislation. The most remarkable fact for users of data related to coastal environment is the open access to the geographical information generated in this plan.

[39] http://www.recursosmarinos.net/gis last accessed 10 May 2012
[40] http://www.xunta.es/litoral/ last accessed 10 May 2012

Moreover, this information can be directly usable in GIS software [41] letting these data be exploited by other users.

The regional government is redefining its role with regard to the geographical information, promoting the unification of the information, the open access, the generation of new cartographic information and the improvement of the old cartography as well as the promotion and development of Free-Libre Open Source Software (FLOSS) (Borobio-Sanchiz, 2011). However the current economic situation slows down the advance of this project.This scenario is quite different from the one that motivated the first chapter of this thesis. Nevertheless, the Spatial Data Infrastructure of Galicia (IDEG) is very recent and a lot of work needs to be done especially on the littoral where the scarce of geographical products continues to be significant.

A second research line carried out in this thesis was directed to the assessment of passive remote sensing sensors to study macroalgal communities. During this thesis the use of multispectral sensors (SPOT-4), spaceborne hyperspectral sensors (CHRIS) as well as airborne hyperspectral sensors (AHS and CASI-2) were assessed to map macroalgal communities on the Galician coast. Moreover, the results obtained contribute to the generation of spatial data regarding seaweeds.

The results achieved in this study showed that the multispectral sensor SPOT-HRVIR was successful in detecting the presence of brown macroalgal communities until 10 m depth. However, the relatively low spectral and spatial resolution did not let the differentiation between macroalgae groups (green, brown and red). SPOT-HRVIR presents four spectral bands and only the two first XS1 (500-590 nm) and XS2 (610 to 680 nm) are useful for the detection of submerged substrates due to the water column absorption at infrared wavelengths. On the other hand, its spatial resolution lets detect only macroalgal homogenous assemblages larger than its pixel size (20 m). For these reasons, this sensor was used with success to map large homogeneous assemblages worldwide (Augenstein et al., 1991; Chauvaud et al., 2001; Pascualini et al., 2005 or Torrusio, 2009). On the Galician coast, some macroalgal species such as *Laminaria* spp., *Cystoseira baccata* or *Sargassum muticum* can form large homogenous assemblages detectable by SPOT-4 satellite. However, its sensor is not able to differentiate between species. In spite of its low spectral resolution and medium spatial resolution, each image can cover 60x60 km. For this reason, this sensor can be useful for studies at regional scale.

On the other hand, the airborne hyperspectral sensor CHRIS-PROBA presents 18 spectral bands from 411 to 1019 nm, 17 m of pixel size and a swath of 13x13 km. Its spectral characteristics improve the ability of macroalgal groups differentiation obtained with SPOT-4 satellite. However, during the development of this work we noticed that after atmospheric correction some of the spectral bands presented anomalous values and they were not included in the analyses. The difficulty to process CHRIS data to Level 2 was also reported by others authors like Alonso et al. (2009) perhaps due to the experimental nature of this sensor. Comparing the spectral configuration of CHRIS mode 2 to MERIS it can be observed that CHRIS

[41] http://www.xunta.es/litoral/web/index.php/descargables last accessed 10 May 2012

sensor has 14 spectral bands between 400 and 750 nm whereas MERIS has only 9 bands. Previous studies using MERIS reported its success in order to differentiate green, brown and red macroalgae (Kutser et al., 2006a). Better spectral resolution and much better spatial resolution allow expecting that CHRIS sensor mode 2 was more suitable than MERIS to map macroalgae communities. However, spectral problems in some bands of CHRIS in this study did not let us exploit the maximal spectral capabilities. This assumption is also confirmed in the study carried out by Pauly et al. (2011) who mapped green, brown and red macroalgae in intertidal regions and shallow waters.

CHRIS-PROBA offers a specific capacity for multiangular measurements, that has been used effectively in terrestrial studies (Begiebing and Bach, 2004; Sykioti et al., 2011) and it is especially effective in terrains with different slopes. Multiangular images were also used for water quality studies (Van Mol and Ruddik, 2004; Ruíz-Verdú et al., 2005) where parameters of the water surface where analysed. However, the multiangular capacity of CHRIS-PROBA is not an advantage in the case of benthic habitat mapping. At different angles from the nadir, light has to penetrate longer distances in water column. Water and its constituents absorb and scatter light strongly and have a strong impact on the spectral signatures of benthic habitats. Different studies (Vahtmäe et al. 2006; Kutser et al. 2006b) show that small variations in water depth (the distance that light has to travel to and from the substrate) have a significant impact on the possibility to recognise different bottom types. Besides, viewing water bodies under angles other than nadir can increase the amount of sun and sky glint significantly. Pauly et al. (2011) and Méndez et al. (2011), the only references found with regard to mapping coastal bottom using CHRIS sensor, also excluded these images from their studies. Thus, CHRIS-PROBA sensor presents an advantage in the differentiation of macroalgal groups with respect to multispectral sensors like SPOT-4. However, the cover of each image is much lesser than SPOT-4 involving a limitation in the mapping at regional scales. Nevertheless, the analysis carried out in this thesis shows that the CHRIS spatial resolution is not sufficient to map in detail the different macroalgal groups (green, brown and red) because benthic cover on the Galician coast is quite heterogeneous.

The assessment of the airborne hyperspectral sensors to map macroalgal communities in the Ría de Vigo was carried out by means of an image-based method and physical-based methods. Results obtained using AHS shows that this sensor can separate between the three macroalgal groups when they are emerged. However, once the substrates are submerged it is not possible the differentiation between brown and red macroalgae. Results obtained for the CASI-2 sensor using a bio-optical model showed better results. Using this sensor the three macroalgal groups could be separated until 4 m depth. This can be explained by the different position of the spectral bands in both sensors as well as by the image noise present in AHS images. As it was reported by Mumby et al., (1997) airborne sensors usually have higher spatial and spectral resolution than satellite sensors, providing more spectral information on pure targets, and thus greater accuracy in detailed habitat mapping. Spatial resolution was around 2.5 m for AHS sensor and 1 m for CASI-2 sensor and both present a swath of several meters, much lower than satellites.These characteristics let the mapping of benthic shallow habitat in detail at local scales.

After the work carried out in this thesis, if we have to recommend a sensor for the study of macroalgal communities on the Galician coast we could say that the best choice will depend on the specific objectives to achieve in each specific study. As it was shown in this thesis multispectral satellites like SPOT-4 or even spaceborne hyperspectral sensors like CHRIS-PROBA can be useful to map macroalgal communities at a regional scale without much detail. Multispectral sensors could be useful as well for retrospective analyses and for monitoring these communities in the future due to its archive data and its revisit time. On the other hand, for more detailed studies higher spectral and spatial resolution are needed. In this case the spatial resolution is more critical as it was shown by Vahtmäe and Kutser (2007). Moreover, all these assessments should be carried out taking into account the available budget. Some initiatives such as Third-Party Missions of ESA or EUFAR Program let the scientific community access to remote sensing data without charge. In other cases, the acquisition of remote sensing data can result prohibitive especially in images of high resolution.

In spite of the high potential of remote sensing and GIS techniques it should be taken into account that resulting macroalgal or habitat maps only represent a snapshot in time and the reliability of their representation at any subsequent time will depend on the degree of natural variability present in the area shown on the map (MESH, 2008). Other than potential temporal changes, there are other limitations to the nature of this habitat information, imposed by the way data are collected, interpreted, displayed and stored. These limitations must be understood since they have profound implications on the design of a mapping programme so that the end user's expectations of habitat mapping are realistic (MESH, 2008).

To research and efficiently manage benthic habitats a continuous data actualization is needed. For this reason the interoperability and promotion of collaboration as well as the sharing of information between users would be a good option in the study of shallow benthic habitats. In last years this trend is gaining importance and new Free-Libre Open Source Software initiatives are appearing because they guarantee the interoperability in a long-term sustainable way. Some examples that could be mentioned here would be MapServer that is an Open Source platform for publishing spatial data and interactive mapping applications to the web. Some important projects like MESH (Mapping European Seabeds Habitats) have bet for this platform to publish its data. The MESH webGIS is a purpose built interactive mapping website which displays these collated data and allows users to access their associated metadata (MESH, 2008). The resulting website delivers significant volumes of habitat mapping data to the public domain. Making the additional effort to share maps on the internet will significantly expand the seabed habitat map resource available to end-users to the mutual benefit of all, and help better manage human activities promoting a sustainable development.

Moreover, the use of remote sensing and GIS are growing at the moment. During last the years new satellites such as WorldView-2, Formosat-2, Rapid-eye, etc. have been launched. These satellites improve the spatial and spectral resolution of the satellites already operative. This technological development seems to continue in the future as it is expected the launch of new satellites. For this reason, the possibilities of mapping shallow benthic habitats and its level of detail is nowadays unpredictable.

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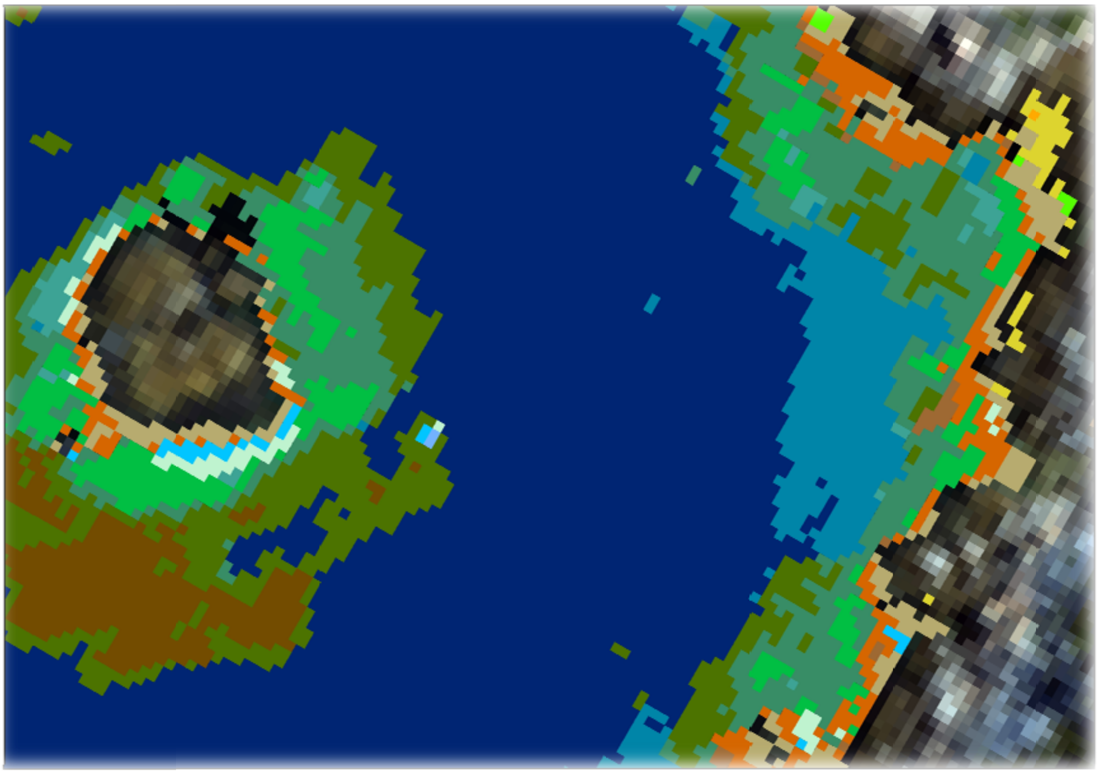

CONCLUSIONS

CONCLUSIONS

- Remote sensing and Geographical Information Systems are potential tools to study coastal environments as it was proven in the present thesis. However, in Galicia there is a lack of studies in this sense compared with other parts of the world, especially in the coastal zone. For this reason, the work carried out in this thesis can be used as basis for future studies in the mapping of shallow benthic habitats in this zone. The change in data policy by Galician government that promotes the free access to public data can be key in the development of a public infrastructure of geographical data as well as in the development of new studies using these techniques.

- Geographical Information Systems are a potential tool for the generation of shorelines. However, a shoreline has to be understood as a dynamic limit between terrestrial and coastal zone and continuous actualizations are required to maintain it updated.

- Multispectral sensors of medium spatial resolution like the ones located in the SPOT-4 satellite can be used with success in the mapping of homogeneous assemblages of brown macroalgae, larger than its pixel size, until 10 m depth. The differentiation of emerged rocky, emerged sandy and submerged sandy substrates is also possible using this kind of sensors.

- The spaceborne hyperspectral sensor CHRIS-Proba allows the differentiation of *shallow submerged sand*, *deep submerged sand*, *macroalgae shallower than 5 m* and *macroalgae between 5 and 10 m*. The differentiation between the three macroalgal groups (green, brown and red) is expected to be possible on the Galician coast. However, the differentiation of brown and red macroalgae was not possible in this study due to the presence of anomalous values in some spectral bands. The experimental nature of this sensor can sometimes difficult the extraction of information from the images. On the other hand, CHRIS spatial resolution is not sufficient to map in detail the different macroalgal groups because benthic cover on the Galician coast is quite heterogeneous. Green and red macroalgae do not usually form large enough homogeneous belts in the study area to be detected by CHRIS pixel size. For this reason, CHRIS could be considered a suboptimal sensor to map heterogeneous macroalgal patches.

- The apparition of sun glint can difficult the interpretation and classification of images. VIR-NIR index can be used with success to correct sun glint effect in CHRIS images.

- The multiangular capacity of CHRIS-Proba is not an advantage in the case of benthic habitat mapping. Under other angles than the nadir, light has to penetrate longer distances in water column. Water and its constituents absorb and scatter light strongly and have a strong impact on the spectral signatures of benthic habitats. On the other hand, viewing water bodies under angles other than nadir can increase the amount of sun and sky glint significantly.

- Bio-optical modelling can be used as a successful alternative for the assessment or classification of remote sensing images on Galician waters. Acquisition of hyperspectral images sometimes involves a high economic investment and there is no prior guarantee of their utility. Physics-based methods like bio-optical models are an alternative to assess sensors without purchasing the images. However, it should be taken into account that results obtained with the model are theoretical. For this reason processes such as sun glint, swell, noise, etc. need to be considered in a real image classification.

- The airborne hyperspectral sensor AHS can be useful in the differentiation of the three macroalgae groups when they are emerged. However, it is not possible to difference between red and brown macroalgae when they are submerged. These results are consequence of the multispectral behavior in the visible region of the electromagnetic spectrum and the noise present in the analysed images. The AHS spatial resolution is useful in the differentiation of the three macroalgal groups. However its spectral resolution could be a limitation for benthic mapping in shallow waters depending on the aim of the study. In our case a differentiation between green and brown macroalgae was possible until 5 m whereas sandy bottoms could be differentiate until 8 m due to its higher reflectance values.

- Using the CASI-2 sensor green, brown and red macroalgae as well as sand could be differentiated from each other when they are emerged. On the other hand, when substrates are submerged, the bio-optical simulations showed that using CASI-2 sensor, the three macroalgal groups (green, brown and red) could be separated from each other until 4 m. Moreover, macroalgal groups were separated from sandy bottoms until 12 m. Species differentiation within a group using CASI-2 spectral bands shows difficulties. Their spectral signal is highly correlated due to their common chemical composition and on the other hand exist a high intra-specific variability. Of the macroalgae species analysed *Codium tomentosum*, *Laminaria saccharina* and *Corallina officinalis* are the most differentiable. Differences in the infrared part of the spectrum could give more information about differentiation at the species level; however these wavelengths are lost when substrates are submerged.

- The classifiers that showed the best results in the analysed images were Maximum Likelihood and Spectral Angle Mapper (SAM) based on training areas established during field work or spectral data, respectively. Visual interpretation also shows good results. However, this latter method requires a high knowledge of the study area to determine an appropriate class and for the correct interpretation of the image.

- The impossibility of differentiate between brown and red macroalgae in the subtidal zone is not a very important handicap on the Galician coast because of the macroalgae species composition in the area. Large-sized brown macroalgae dominate this zone in dense populations and can reach 100% of coverage. Red algae are only present as undergrowth that cannot be detected by remote sensing sensors.

- The correct choice of a sensor not only on the Galician coast but also in other locations will depend on each specific study and on the aim to achieve. However, in heterogeneous environments such as occur on the Galician coast the high spatial resolution is preferable to the high spectral resolution.

- Up to now, studies on benthic macroalgae carried out on the Galician coast were based on conventional methods (transects, quadrats...) based on direct observation and covering small areas. Proper large scale management of this area is not possible as the macroalgal cover data is available only for certain smaller areas and there is a lack of continuous data in space and time. In this study we have shown that remote sensing images can be an alternative to conventional methods in the creation of accurate thematic maps. However, it is necessary to take into account that the resulting maps only represent a snapshot in time and the reliability of their representation at any subsequent time will depend on the degree of natural variability present in the area shown on the map.

SUMMARY

IN SPANISH

SUMMARY IN SPANISH

INTRODUCCIÓN

Las zonas costeras representan la transición entre el ambiente terrestre y el acuático siendo uno de los ecosistemas más dinámicos y productivos de la Tierra. Las comunidades de algas bentónicas juegan un papel clave en los ecosistemas costeros debido a sus funciones ecológicas. Estas comunidades son esenciales como hábitat para muchos organismos (Birkett et al. 1998; Cacabelos et al. 2010), como zonas de apareamiento y cría de un gran número de especies, incluso comerciales como el bacalao (*Gadus morhua*) o el abadejo (*Pollachius pollachius*) (Sjøtun et al., 1993, Borg *et al*. 1997; Shaffer 2003). Además de zonas de alimentación (Velando and Freire, 1999; Lorentsen *et al*. 2004) y refugio (Bushmann 1990; Gotceitas *et al*. 1997). Otro aspecto relevante es su importante contribución a la producción primaria, por ejemplo algunos estudios sobre bosques de Laminariales, como los presentes en la costa gallega, muestran producciones mayores a 4000gC/m^2·año (Mohammed and Fredriksen 2004). Estas comunidades también contribuyen a la estabilización del sedimento y a la protección del litoral (Madsen *et al*. 2001) además de ser indicadores eficaces del estado ecológico de las comunidades costeras (Juanes et al., 2008). Por otra parte, en los últimos años se ha incrementado el interés por el uso comercial de algunas especies de algas en muchas partes del mundo (Vasquez 2008; Vea and Ask 2011). Esta situación también ha producido en Galicia donde se han establecido planes de explotación específicos.

Debido a su importancia ecológica y económica, existe la necesidad de métodos que permitan reunir información cualitativa y cuantitativa acerca de las comunidades bentónicas para su eficiente valoración, monitorización y gestión. El uso de la teledetección presenta ciertas ventajas respecto a métodos tradicionales y su utilización se encuentra bien establecida para tal fin. Entre estas ventajas podemos mencionar que este tipo de técnicas no son invasivas, permiten estudiar áreas extensas y cartografiar zonas inaccesibles además de proporcionar una cobertura repetitiva. Esta última característica permite la generación de datos de archivo para la detección de cambios a lo largo del tiempo. Además los datos son digitales y pueden ser fácilmente integrados en Sistemas de Información Geográfica (SIG) para posteriores análisis (Green and King, 2005; Cassata and Collins, 2008). Mientras que la teledetección constituye una fuente de información que puede ser utilizada para describir y monitorizar una elevada variedad de sistemas tanto a escala local como global, los SIG pueden ser utilizados como herramientas de análisis espacial proporcionando una plataforma para la integración, síntesis y modelado. Esta información puede ser utilizada para el apoyo de la toma de decisiones, esencial en muchas aplicaciones costeras.

Sin embargo, a pesar de estas ventajas, el uso de la teledetección en el medio marino puede estar algunas veces sobrevalorado dando lugar a unos resultados decepcionantes para el usuario por no haber considerado ciertas limitaciones. Por esta razón es necesario tener en cuenta que por ejemplo sólo ciertas longitudes de onda puden penetrar en la columna de agua, la existencia de pixeles de mezcla o la atenuación atmosférica (Holden and LeDrew, 1998). La importancia de cada fuente de error o limitación dependerá del objetivo del estudio y variará dependiendo del sensor. Otros factores que deberían ser tenidos en cuenta son las condiciones meteorológicas presentes en el área de estudio. La presencia de nubes puede provocar que las imágenes sean inservibles o en el caso de un estudio temporal una importante reducción de las imágenes utilizables.

Las resoluciones espectral y espacial también juegan un papel importante en el cartografiado de las comunidades de algas. Holden and LeDrew (1998) afirmaron que la resolución espectral es importante debido a la limitada penetración de algunas longitudes de onda en el agua. Por otra parte, es necesario considerar también la anchura de las bandas espectrales debido a que algunas características pueden pasar desapercibidas debido a unas bandas demasiado anchas. Las comunidades de algas pueden llegar a ser bastante heterogéneas lo que requiere el uso de una elevada resolución espacial que permita detectar las diferentes manchas de algas así como reducir el efecto de los píxeles de mezcla.

La teledetección se ha aplicado en muchas partes del mundo para el cartografiado de las comunidades de algas en una gran variedad de condiciones ambientales aunque el número de estudios aguas claras puede considerarse mayor. Existen estudios que utilizan para este propósito una gran variedad de sensores multiespectrales e hiperespectrales así como modelos bio-ópticos. Algunos ejemplos serían los estudios realizados por Kutser et al. (2003, 2006a) y Karpouzli et al., (2004) que cartografiaron algas asociadas a los arrecifes de coral, Pe'eri et al. (2008) que cartografiaron algas y fanaerógamas en un ambiente estuárico, Vahtmäe et al. (2006) and Kutser et al, (2006b) que cartografiaron algas en aguas turbias o Henning et al. (2007) que lo hicieron en intermareales rocosos.

En España el uso de técnicas de teledetección en la zona terrestre está bien reconocido y existen numerosos estudios basados en usos del suelo (e.g. Viedma et al., 2006; García-Ruíz, 2010), áreas quemadas (e.g. Chuvieco and Congalton, 1989; López-García and Caselles, 1991; Merino-de-Miguel et al., 2010), aguas interiores (e.g. López-García and Caselles, 1990; Lavery et al., 1993), etc. Sin embargo, el número de estudios aplicados a la zona costera y especialmente al cartografiado de hábitats bentónicos someros decrece considerablemente. Por esta razón las referencias científicas relacionadas con estas aplicaciones son escasas. Entre ellas podemos mencionar los estudios realizados por Fornes et al. (2006) quienes cartografiaron *Posidonia oceanica* utilizando el sensor multiespectral IKONOS, Méndez et al. (2011) que cartografiaron *P. oceanica* y *Cymodocea nodosa* utilizando los sensores hiperespectrales CASI y CHRIS o el estudio llevado a cabo por Chust et al. (2010) utilizando LIDAR para el cartografiado de hábitats costeros en un estuario Vasco.

En Galicia la escasez de estudios relacionados con el cartografiado bentónico utilizando teledetección es más acusado que a nivel nacional. Algunos de los estudios localizados en la zona costera están relacionados con el seguimiento de mareas rojas (e.g. Mosquera et al., 2006), vertidos (e.g. Torres-Palenzuela et al. 2006) o fenómenos de afloramiento (e.g. Spyrakos et al., 2011) a escala regional. Sin embargo, la única referencia encontrada en relación al cartografiado bentónico fue el estudio llevado a cabo por Catoira et al. en 1993. Estos autores realizaron un trabajo preliminar utilizando imágenes multiespectrales Landsat 5TM sin obtener resultados positivos. Por esta razón, el trabajo realizado en esta tesis abre una nueva línea de investigación en la costa gallega en relación a la utilización de este tipo de técnicas aplicadas al cartografiado bentónico.

OBJETIVOS

En los últimos años el Grupo de Recursos Marinos y Pesquerías de la Universidad de A Coruña ha realizado un gran esfuerzo para integrar y completar una serie de información geográfica, procedente de diferentes ámbitos relacionados con el medio costero[42]. En este contexto se establece el primer objetivo general de esta tesis y consiste en la generación de una infraestructura de datos digitales georreferenciados que constituya una cartografía básica para el análisis científico y gestión del medio marino.

De este objetivo general se derivan los siguientes objetivos específicos:

- Digitalización de una línea de costa detallada y precisa de Galicia mediante el uso de Sistemas de Información Geográfica (SIG). Desarrollo y publicación de una metodología en la que se recoja el indicador empleado, su definición y los criterios seguidos durante el trazado. División de la línea de costa digitalizada atendiendo al tipo de unidad fisiográfica litoral (costa arenosa, costa rocosa, marisma, estuario y estructuras artificiales)

El segundo objetivo general consiste en la valoración de técnicas de teledetección para el cartografiado de las comunidades de algas en la costa gallega. Las comunidades de algas estudiadas aquí son aquellas que pueden formar asentamientos homogéneos mayores en extensión que el tamaño de píxel del sensor a valorar.

De este objetivo general se derivan los siguientes objetivos específicos:

- Desarrollo y validación de una metodología para el cartografiado de los bosques de Laminariales intermareales y submareales utilizando el satélite multiespectral SPOT-4 (*Satellite Pour l'Observation de la Terre*).

- Valoración de la utilización del sensor hiperespectral CHRIS (*Compact High Resolution Imaging Spectrometer*) instalado en el satélite PROBA para el cartografiado de comunidades de algas y otros substratos bentónicos en la zona costera así como la valoración de la posible diferenciación entre los grupos de algas verdes, pardas y rojas.

- Valoración de la utilización del sensor aeroportado AHS (*Airborne Hyperspectral Scanner*) en el cartografiado de algas así como la posible diferenciación a nivel de grupos de algas (verde, pardas y rojas) o incluso a nivel especie.

- Valoración de la utilización del sensor aeroportando CASI-2 (*Compact Airborne Spectographic Imager*) en la discriminación de comunidades de algas mediante la

[42] http://www.recursosmarinos.net/gis last accessed 10 May 2012

utilización de un modelo bio-óptico para aguas poco profundas. La diferenciación espectral entre sustratos bentónicos será analizada y el límite de profundidad para su diferenciación establecido.

- Comparar los resultados obtenidos con los diferentes sensores y establecer recomendaciones para la utilización de métodos de teledetección en el estudio de las comunidades de algas en la costa gallega.

Cada capítulo de esta tesis ha sido redactado de forma independiente por lo que pueden ser leídos individualmente. Debido a esto algunas de las partes pueden encontrase repetidas en el conjunto del documento.

CAPÍTULO I. Generación de una línea de costa digital de Galicia (NO España) a gran escala, utilizando fotointerpretación y segmentación dinámica.

La línea de costa, entendida como el límite de contacto entre la superficie emergida y la oceánica, constituye un elemento geográfico primordial para cualquier estudio desarrollado en la zona litoral. Aunque existe cierto consenso en su definición, ésta da lugar a multitud de criterios específicos para su delimitación en función del indicador empleado, de la fuente de información utilizada o del sistema de digitalización.

El objetivo principal de este estudio consistió en la digitalización de una línea de costa del litoral gallego (1:750) utilizando ortofotos como fuente de información espacial, definiendo en el proceso unos criterios de digitalización específicos. Además se han generado capas de información geográfica digital derivada de la línea original y se ha aplicado segmentación dinámica a toda la información digitalizada. Tanto la información cartográfica como la metodológica se encuentran accesibles de forma detallada en la dirección: http://gis.recursosmarinos.net

CAPÍTULO II. Teledetección con SPOT-4 para el cartografíado de bosques de *kelp* en aguas turbias de la plataforma atlántica del Sur de Europa.

El uso de técnicas de teledetección en el cartografiado temático de áreas marinas de gran extensión se ha incrementado en los últimos años y muchos investigadores han utilizado estas técnicas de forma exitosa en cartografiado bentónico de aguas claras. Sin embargo, las áreas de elevada complejidad óptica presentan importantes limitaciones que están siendo gradualmente resueltas debido a los recientes avances tecnológicos. En este contexto, el principal objetivo de este capítulo consiste en desarrollar y validar una metodología para el cartografiado intermareal y submareal los bosques de *kelp* presentes en la costa gallega (NO España), basada en imágenes del satélite SPOT-4 (Satellite Pour l'Observation de la Terre). Para ello se aplicaron tres métodos de análisis: interpretación y análisis visual, clasificación no supervisada (cluster) y clasificación supervisada (Spectral Angle Mapper y Maximum Likelihood). Los porcentajes de clasificación fueron mayores al 70% en todos los sustratos utilizando interpretación visual y clasificación de máxima probabilidad.

CAPÍTULO III. Cartografiado de las comunidades de macroalgas bentónicas en la zona costera utilizando imágenes CHRIS-PROBA modo 2.

La importancia ecológica de las comunidades de algas bentónicas en los sistemas costeros ha sido ampliamente reconocida y la aplicación de teledetección para el estudio de estas comunidades presenta ciertas ventajas con respecto a los métodos *in situ*. En este capítulo se utilizaron tres imágenes del sensor CHRIS-Proba para el análisis de la distribución de macroalgas en el Seno de Corcubión (NO España). La utilización de este sensor supone un desafío dado a que su programa de diseño, construcción y despliegue es un intento de seguir los principios de "más rápido, mejor y más barato". Con el fin de valorar la aplicación de este sensor en el cartografiado de macroalgas, se realizaron dos tipos de clasificaciones: Maximum Likelihood y Spectral Angle Mapper (SAM). El clasificador Maximum Likelihood mostró resultados positivos, alcanzando porcentajes globales de precisión mayores al 90% y coeficientes kappa mayores a 0.80 para las clases arena sumergida poco profunda, arena sumergida profunda, macroalgas de profundidad menor a 5 m y macroalgas entre 5 y 10 m. La diferenciación entre grupos de macroalgas utilizando clasificaciones SAM mostraró resultados positivos para algas verdes aunque la diferenciación entre algas pardas y rojas no fue clara en este área de estudio.

CAPÍTULO IV. Valoración del sensor AHS (Airborne Hyperspectral Scanner) para el cartografiado de comunidades de macroalgas en la Ría de Vigo y la Ría de Aldán.

La Ría de Vigo y la Ría de Aldán presentan una elevada riqueza biológica que se refleja en el número de áreas de protección ambiental reconocidas como pueden ser el Parque Nacional Islas Atlánticas y cinco lugares de interés comunitario (LICs). Las comunidades de algas bentónicas juegan un papel importante en estos ecosistemas debido a sus funciones ecológicas. En este capítulo se valoró la utilización de teledetección en el cartografiado de comunidades de algas en la Ría de Vigo y en la Ría de Aldán utilizando un modelo bio-óptico e imágenes del sensor Airborne Hyperspectral Scanner (AHS) (NO España). El modelo fue aplicado a los grupos de algas debido a la imposibilidad de diferenciación a nivel de especie utilizando este sensor. Los resultados obtenidos indican que la separación entre los tres grupos de macroalgas (verdes, pardas y rojas) así como arena es posible cuando estos sustratos están emergidos. Sin embargo, estas diferencias se reducen rápidamente con el incremento de la profundidad. Utilizando las imágenes AHS se realizaron dos tipos de clasificaciones: Maximum Likelihood y Spectral Angle Mapper (SAM). Maximum Likelihood mostró resultados positivos alcanzando porcentajes globales de precisión superiores al 95% y coeficientes kappa superiores a 0.90 para las clases: arena poco profunda, arena profunda, roca emergida, algas emergidas y algas sumergidas. Posteriormente se realizó una clasificación de los sustratos de arena y algas de forma independiente utilizando SAM. Estas clasificaciones mostraron resultados positivos en la diferenciación de algas verdes y pardas hasta 5 m de profundidad y clara diferenciación entre los sustratos arena y algas. Sin embargo, la diferenciación entre algas pardas y rojas sólo fue detectada cuando ambos sustratos se encuentran emergidos.

CAPÍTULO V. Valoración del sensor hiperespectral CASI-2 en la discriminación de macroalgas en la costa de la Ría de Vigo (NO España) utilizando espectroscopía de campo y librerías espectrales modeladas.

La teledetección hiperespectral constituye una herramienta importante en el cartografiado de los hábitats bentónicos poco profundos. Sin embargo, la adquisición de imágenes hiperespectrales implica en ocasiones una gran inversión económica y no existe una garantía previa de su utilidad. Los métodos de base física como los modelos bio-ópticos son una alternativa en la valoración de sensores sin la necesidad de adquisición de imágenes. En este estudio, se evaluó un modelo bio-óptico simple para aguas someras con el fin de valorar diferencias entre las comunidades de algas. Análisis estadísticos previos muestran que sólo unas pocas especies parecen claramente diferenciables: *Codium tomentosum*, *Laminaria saccharina* y *Corallina officinallis*. Así, el modelo bio-óptico fue realizado para los grupos taxonómicos donde las firmas espectrales son más consistentes en forma. Utilizando el sensor CASI-2 se pudieron diferenciar entre sí algas verdes, pardas y rojas así como arena cuando estos sustratos se encuentran emergidos. Por otra parte, cuando los sustratos se encuentran sumergidos, las simulaciones bio-ópticas mostraron que utilizando el sensor CASI-2, los tres grupos macroalgales pudieron ser diferenciados entre sí hasta 4 m de profundidad. Algas verdes y pardas fueron diferenciables de agua profunda hasta 6 m de profundidad mientras que las algas rojas lo fueron hasta 5 m. Los grupos macroalgales fueron diferenciados de los fondos arenosos hasta una profundidad de 10 m.

DISCUSIÓN GENERAL

El conocimiento de la distribución espacial, calidad y cantidad de los recursos bentónicos es fundamental en el entendimiento de los ecosistemas marinos y en la gestión de las actividades humanas para el desarrollo sostenible y el mantenimiento del ecosistema marino (MESH, 2008).

Los mapas temáticos detallados de los hábitats bentónicos facilitan la conservación de estos paisajes, incrementando el entendimiento de los factores que pueden provocar cambios ambientales. Estos mapas proporcionan información georreferenciada sobre el tipo de cobertura biológica en el ambiente marino y son más útiles para la gestión y planificación espacial cuando son creados a una escala apropiada (Wedding et al., 2011). Los mapas bentónicos están ampliamente reconocidos como un punto crítico para la gestión efectiva de recursos marinos (Kostylev et al., 2001). En ausencia de este tipo de información, los responsables de la toma de decisiones se encuentran a menudo limitados sobre los efectos que las diferentes actividades puedan tener sobre los hábitats marinos (Pandian et al., 2009). A pesar de los muchos estudios realizados en relación a la distribución espacial de las algas marinas, puede resultar llamativa la afirmación realizada por Nature Editorial (2008) sobre la ausencia o imprecisión de la información. Esta cuestión fue también mencionada por Pauly y De Clerk (2010) quienes demostraron una ausencia notable de datos espaciales en estudios de algas hasta la fecha.

Como ha sido anteriormente mencionado, SIG y teledetección tienen un uso potencial en la generación de información digital geográfica. Sin embargo, en el momento del planteamiento de esta tesis la falta de información en este campo era notable en Galicia. Poca información estaba disponible para los usuarios y en la mayoría de los casos era de escaso detalle o el proceso de adquisición demasiado arduo. Estas limitaciones relacionadas con la mala organización y la política restrictiva de los datos han sido recientemente reconocidas por el gobierno (Borobio Sanchiz, 2011). Por esta razón, esta tesis fue en un principio diseñada como una contribución a la generación de datos geográficos digitales para la zona litoral, donde la escasez era y siguie siendo más significante.

De esta manera, el primer capítulo de la tesis fue dedicado a la digitalización de una línea de costa para el litoral de Galicia. La localización de la línea de costa y su posición cambiante a lo largo del tiempo son de importancia clave para los científicos costeros, ingenieros y administradores (National Research Council, 1990; Douglas and Crowell, 2000). Como fue mencionado por Boak and Turner (2005) tanto la gestión costera como el diseño de ingeniería requieren información sobre donde está la línea de costa, donde ha estado en el pasado y dónde se predice que estará en el futuro. Por otra parte, los científicos que desarrollan su trabajo en la zona costera necesitan establecer una delimitación para su área de estudio. De esta manera, en este capítulo se digitalizó una línea de costa a escala de 1:750. Esta línea de costa permitió la generación de información derivada tal como marismas, estuarios, islas y la segmentación dinámica en tipologías costeras en relación al tipo de sustrato. Junto con esta información geográfica se creó también una librería de criterios. Esta librería incluye los criterios que fueron seguidos durante la digitalización en cada tipo de sustrato: estructuras artificiales, costa rocosa y acantilada, costa arenosa y playas, marismas e islas. Además, se incluyó un sexto grupo que recoge los criterios seguidos en casos particulares y que no pudieron ser incluidos en los grupos anteriormente mencionados. De esta manera, se conocería el proceso de la generación de estos datos pudiendo ser replicado. Toda esta información ha sido publicada en internet[43] y compartida bajo una licencia Creative Commons.

Hoy en día, el gobierno gallego es consciente de la importancia de la información geográfica y actualmente está realizando esfuerzos para generar bases de datos geográficas estandarizadas donde los usuarios puedan acceder a este tipo de datos (Borobio Sanchiz, 2011). En este sentido, se creó la Infraestructura de Datos Espaciales de Galicia (IDEG) (Directiva 2007/2/EC el 14 Marzo de 2007), la cual sigue la infraestructura establecida para la información espacial en la Comunidad Europea (INSPIRE). En la IDEG se reúnen, tratan e integran datos, metadatos y servicios vinculados a Galicia susceptibles de ser localizados geográficamente.

Uno de los objetivos más importantes de la IDEG es proporcionar acceso a los datos a todas las autoridades públicas, sector privado y al público en general proporcionando información, servicios y metadatos geográficos estandarizados así como la posibilidad de integrar esta información en una IDE común. El link http://sitga.xunta.es/sitganet/ permite al usuario identificar, localizar, seleccionar y acceder a una gran variedad de recursos. En este sitio web, se pueden encontrar productos cartográficos relacionados con el territorio gallego como pueden ser hidrografía, coberturas del suelo, límites, población, etc. Sin embargo, los productos cartográficos relacionados con la zona litoral continúan siendo escasos y aparecen como derivados de otros y no generados específicamente para esta zona. En relación a la información geográfica de la zona litoral, es necesario mencionar la reciente aprobación del Plan de Ordenación Litoral (2010)[44]. Este plan ha generado datos geográficos que incluyen información acerca del paisaje, medioambiente, infraestructuras, ocupación y usos del suelo,

[43] http://www.recursosmarinos.net/gis last accessed 10 May 2012
[44] http://www.xunta.es/litoral/ last accessed 10 May 2012

urbanización y legislación. Además, esta información puede ser directamente utilizable en programas de SIG[45] permitiendo la explotación de los datos por parte de otros usuarios.

El gobierno autonómico está redefiniendo su papel en relación a la información geográfica, promoviendo la unificación de la información, el libre acceso, la generación de nueva información cartográfica y la mejora de la antigua así como la promoción y desarrollo de Free-Libre Open Source Software (FLOSS) (Borobio Sanchiz, 2011). Sin embargo, la actual situación económica ha reducido el avance de este proyecto. Este escenario es bastante diferente al que motivó el primer capítulo de esta tesis. No obstante, la Infraestructura de Datos Espaciales de Galicia (IDEG) es muy reciente y será necesario un gran esfuerzo para su puesta a punto, especialmente en el litoral, donde la escasez de productos geográficos es notable.

Una segunda línea de investigación realizada en esta tesis fue dirigida a la valoración de sensores de teledetección pasivos para el estudio de comunidades de algas. Durante la realización de esta tesis se valoraron diversos sensores multiespectrales (SPOT-HRVIR), sensores hiperespectrales espaciales (CHRIS-Proba) y sensores aeroportados (AHS y CASI-2). Además, los resultados obtenidos contribuyen a la generación de datos espaciales referentes a las algas presentes en el litoral gallego.

El satélite multiespectral SPOT-4 mostró resultados positivos en la detección de la presencia de comunidades de algas pardas hasta 10 m de profundidad. Sin embargo, la relativamente baja resolución espacial y espectral no permitió diferenciar grupos de algas (verdes, pardas y rojas) entre si. Este satélite presenta cuatro bandas espectrales y sólo las dos primeras XS1 (500-590 nm) y XS2 (610-680 nm) son útiles en la detección de sustratos sumergidos debido a la absorción de longitudes de onda infrarrojas. Por otra parte, su resolución espacial permite solamente detectar asentamientos homogéneos de algas mayores su tamaño de píxel (20 m). Por estas razones, este satélite ha sido utilizado con éxito para el cartografiado de asentamientos homogéneos de algas de gran tamaño (Augenstein et al., 1991; Chauvaud et al., 2001; Pascualini et al., 2005 o Torrusio, 2009). En la costa gallega, existen algunas especies de macroalgas que pueden formar grandes asentamientos homogéneos tales como *Laminaria* spp., *Cystoseira baccata* o *Sargassum muticum* y detectables por el satélite SPOT-4. Sin embargo, este sensor no es capaz de diferenciar a nivel de especie. A pesar de su baja resolución espectral y media resolución espacial, cada imagen pude cubrir 60x60 km. Por esta razón, este sensor puede ser utilizado para estudios a escalas regionales.

Por otra parte, el sensor hiperespectral CHRIS-Proba presenta 18 bandas espectrales que comprenden un rango espectral entre 411 y 1019 nm, 17 m de tamaño de pixel y un *swath* de 13x13 km. Sus características espectrales mejoran la capacidad de diferenciación entre grupos de algas en comparación con las obtenidas por el satélite SPOT-4. Sin embargo, durante el desarrollo de este trabajo se observó que después de la corrección atmosférica algunas de las bandas presentaron valores anómalos y éstas no fueron incluidas en el análisis. La dificultad de procesar los datos CHRIS a nivel 2 ha sido mencionado por otros autores tales como Alonso et al. (2009) debido probablemente a su naturaleza experimental. Comparando la configuración espectral de CHRIS modo 2 y MERIS se observa que el sensor CHRIS tiene 14

[45] http://www.xunta.es/litoral/web/index.php/descargables last accessed 10 May 2012

bandas espectrales ente 400 y 750 nm mientras que MERIS solamente presenta 9 bandas. Estudios previos utilizando MERIS demostraron el éxito de este sensor en la diferenciación de algas verdes, pardas y rojas (Kutser et al., 2006). Una mejor resolución espectral y espacial hace esperar que el sensor CHRIS sea más apropiado que MERIS en el cartografiado de las comunidades algales. Sin embargo, en este estudio los valores ánomalos en algunas bandas de CHRIS no permitieron el máximo aprovechamiento de sus capacidades espectrales. Esta asunción es también confirmada en el estudio realizado por Pauly et al (2011) quienes cartografiaron algas verdes, pardas y rojas en regiones intermareales y de aguas poco profundas.

CHRIS Proba presenta capacidad para la toma de imágenes multiangulares que ha sido utilizada de forma exitosa en estudios terrestres (Begiebing and Bach, 2004; Sykioti et al., 2011) y es especialmente efectivo en terrenos con diferente pendiente. Las imágenes multiangulares fueron también utilizadas para estudios de calidad de agua (Van Mol and Ruddik, 2004; Ruíz-Verdú et al., 2005) donde se estudiaron parámetros de la superficie del auga. Sin embargo, la capacidad multiangular de CHRIS-Proba no es una ventaja en el caso del cartografiado bentónico. Con ángulos differentes al nadir, la luz tiene que penetrar más distancia en la columna de agua. El agua y sus constituyentes absorben y dispersan la luz y este effecto tiene un impacto considerable sobre las firmas espectrales de los sustratos bentónicos.

Diferentes estudios (Vahtmäe et al. 2006; Kutser et al. 2006b) muestran que pequeñas variaciones de profundidad (la distancia que la luz tiene que viajar hacia y desde el sustrato) tienen un impacto importante sobre la posibilidad de reconocer los diferentes tipos de fondo. Además los diferentes ángulos, diferentes del nadir, pueden incrementar la cantidad de sun glint y sky glint. Pauly et al. (2011) y Méndez et al. (2011), las únicas referencias encontradas en relación al cartografiado de fondos costeros utilizando el sensor CHRIS, también excluyeron estas imágenes angulares de sus estudios. Por lo tanto, el sensor CHRIS-Proba presenta una ventaja en la diferenciación de los grupos macroalgales respecto a sensores multiespectrales como el HRVIR de SPOT-4. Sin embargo, la cobertura de cada imagen es mucho menor implicando una limitación en el cartografiado a escalas regionales. No obstante, los análisis realizados en esta tesis muestran que la resolución espacial de CHRIS no es suficiente para cartografiar en detalle los diferentes grupos algales (verdes, pardas y rojas) en la costa gallega, debido a que la cobertura bentónica en esta zona es bastante heterogénea.

La valoración de sensores hiperespectrales para el cartografiado de comunidades algas bentónicas en la Ría de Vigo fue realizada utilizando métodos basados en imágenes así como métodos físicos. Los resultados obtenidos muestran que el sensor AHS es capaz de separar los tres tipos de grupos de algas cuando están emergidos. Sin embargo, cuando las algas se encuentran sumergidas la diferenciación entre algas pardas y rojas no es posible. Los resultados obtenidos para el sensor CASI-2 utilizando el modelo bio-óptico mostraron buenos resultados. Utilizando este sensor se pudieron separar los tres grupos de algas hasta una profundidad de 4 m. Esto puede explicarse debido a la posición de las diferentes bandas espectrales en ambos sensores así como al ruido presente en las imágenes AHS. Como fue mencionado por Mumby et al. (1997) los sensores aeroportados presentan mayor resolución espacial y espectral que los sensores satelitales, proporcionando una mayor información espectral sobre objetivos puros, y así mayor precisión en el cartografiado detallado de hábitats. La resolución espacial del sensor AHS y CASI-2 es de alrededor de 2 m y el *swath* (varios metros) es también mucho menor que el presente en satélites. Estas características permiten el cartografiado detallado de hábitats bentónicos poco profundos a escalas locales.

Después del trabajo realizado en esta tesis, si tuviéramos que recomendar un sensor para el estudio de las comunidades de algas en la costa gallega, podríamos decir que la mejor elección dependerá de los objetivos específicos de cada estudio. En esta tesis se demostró que satélites multiespectrales como SPOT-4 o incluso sensores hiperespectrales espaciales como CHRIS-Proba pueden ser útiles en el cartografiado de comunidades de macroalgas a una escala regional sin demasiado detalle. Los sensores multiespectrales podrían ser de utilidad en la realización de estudios retrospectivos así como en la monitorización de estas comunidades en el futuro debido a la elevada cantidad de datos de archivo y su tiempo de revisita. Por otra parte, para estudios más detallados se necesita una mayor resolución espacial y espectral. En el caso de la costa gallega la resolución espacial es considerada prioritaria al igual que afirmaron Vahtmäe y Kutser (2007). Además, todas estas valoraciones deberían ser realizadas teniendo en cuenta el presupuesto disponible. Algunas iniciativas como por ejemplo *Third-Party Missions* o el Programa *EUFAR* permiten el acceso a los datos de teledetección a la comunidad científica de forma gratuita o a coste de reproducción. En otros casos, la adquisición de datos de teledetección puede resultar prohibitiva especialmente en imágenes de elevada resolución.

A pesar del elevado potencial de las técnicas de teledetección y SIG debería de tenerse en cuenta que los mapas resultantes no solamente representan una imagen instantánea en el tiempo y la fiabilidad de su representación en cualquier momento posterior dependerá del grado de variabilidad natural presente en el área representada en el mapa (MESH, 2008). Aparte de los potenciales cambios temporales, hay otras limitaciones relacionadas con la forma de adquisición de los datos, su interpretación, representación y almacenamiento. Estas limitaciones tienen implicaciones sobre el diseño del programa de cartografiado provocando que las expectaciones del usuario sobre el cartografiado de hábitats sean más realistas (MESH, 2008).

Para investigar y gestionar eficientemente los hábitats bentónicos es necesario una continua actualización de los datos. Por esta razón la interoperabilidad y la promoción de colaboración así como el compartir información entre usuarios serían una buena opción en el estudio de hábitats bentónicos poco profundos. En los últimos años esta tendencia está ganando importancia y nuevas iniciativas *Free-Libre Open Source Software* están apareciendo debido a que garantizan la interoperabilidad a largo plazo de manera sostenible. Algunos ejemplos que podrían ser mencionados aquí serían *MapServer* que es una plataforma *Open Source* para la publicación de datos espaciales y aplicaciones de cartografiado interactivo en la web. Algunos proyectos importantes como *MESH* (*Mapping European Seabeds Habitats*) han apostado por esta plataforma para publicar sus datos. *MESH WebGIS* es un sitio web con el propósito de construir un cartografiado interactivo en donde se pueden visualizar los datos recopilados y permite a los usuarios acceder a sus metadatos asociados (MESH, 2008). El sitio web resultante proporciona un volumen significante de datos sobre el cartografiado de hábitats al dominio público. Haciendo un esfuerzo adicional por compartir los datos en internet se expandirían de forma importante los recursos disponibles para los usuarios finales ayudando así a una mejor gestión de las actividades humanas y promoviendo un desarrollo sostenible.

Además, el uso de la teledetección y SIG así como sus aplicaciones continúa. Durante los últimos años se han lanzado nuevos satélites tales como WorldView-2, Formosat-2, Rapid-eye, etc. mejorando las características técnicas de los ya operativos. Este desarrollo tecnológico parece continuar en el futuro debido a que se espera el lanzamiento de nuevos satélites. Por esta razón, las posibilidades que podrá ofrecer el cartografiado de hábitats bentónicos poco profundos y su nivel de detalle, a día de hoy, es impredecible.

CONCLUSIONES

- La teledetección y los Sistemas de Información Geográfica son herramientas potenciales para el estudio de los ambientes costeros como ha sido demostrado en la presente tesis. Sin embargo, en Galicia existe una falta de estudios en este sentido, especialmente en la zona costera, si lo comparamos con otras partes del mundo. Por esta razón, el trabajo realizado en esta tesis puede ser utilizado como base para futuros trabajos sobre cartografiado de hábitats bentónicos poco profundos. El cambio en la política de datos realizada por el gobierno gallego, dirigida a la promoción del libre acceso a los datos públicos, puede ser clave en el desarrollo de una infraestructura pública de datos geográficos así como en el desarrollo de nuevos estudios utilizando estas técnicas.

- Los Sistemas de Información Geográfica son herramientas potenciales en la generación de líneas de costa. Sin embargo, la línea de costa debería ser entendida como un límite dinámico entre la zona costera y la terrestre por lo que son necesarias continuas actualizaciones que la mantengan permanentemente actualizada.

- Los sensores multiespectrales de resolución espacial media como los presentes en el satélite SPOT-4 pueden ser utilizados con éxito en el cartografiado de asentamientos homogéneos de algas pardas, mayores que su tamaño de píxel, hasta 10 m de profundidad. La diferenciación entre los sustratos roca emergida, arena emergida y arena sumergida es también posible utilizando este tipo de sensores.

- El sensor espacial CHRIS-Proba permite la diferenciación de las clases: arena sumergida poco profunda, arena sumergida profunda, algas de profundidad menor a 5 m y algas entre 5 y 10 m. La diferenciación entre los diferentes grupos de algas (verde, pardas y rojas) se espera posible en la costa gallega. Sin embargo, la diferenciación entre algas pardas y rojas no fue posible en este estudio debido a la presencia de valores anómalos en algunas bandas espectrales. La naturaleza experimental de este sensor puede en ocasiones dificultar la extracción de información a partir de las imágenes. Por otra parte, la resolución espacial de CHRIS no es suficiente para cartografiar en detalle los diferentes grupos algales debido a que el fondo costero en la costa gallega es bastante heterogéneo. En el área de estudio las algas verdes y rojas no forman cinturas homogéneas suficientemente grandes para ser detectadas por el tamaño de píxel de este sensor. Por esta razón, CHRIS podría ser considerado un sensor subóptimo para el cartografiado de parches de algas.

- La aparición de *sun glint* puede dificultar la interpretación y clasificación de las imágenes. El índice VIR-NIR puede ser utilizado con éxito en la corrección de este efecto en imágenes CHRIS.

- La capacidad multiangular de CHRIS-Proba no es una ventaja en el caso del cartografiado bentónico costero. Bajo otros ángulos diferentes al nadir, la luz tiene que penetrar mayores distancias en la columna de agua para alcanzar el fondo. El agua y sus constituyentes absorben y dispersan fuertemente la luz y tienen un gran impacto sobre las firmas espectrales de los hábitats bentónicos. Por otra parte, la observación de los cuerpos de agua bajo otros ángulos diferentes al nadir pude incrementar la cantidad de *sun glint y sky glint*.

- El modelado bio-óptico puede ser utilizado como alternativa en la valoración o clasificación de imágenes de teledetección en las aguas gallegas. La adquisición de imágenes hiperespectrales implica en ocasiones una elevada inversión económica y no existen garantías previas de su utilidad. Los métodos físicos como el modelado bio-óptico son una alternativa a la valoración de sensores sin la adquisición previa de imágenes. Sin embargo, se debería de tener en cuenta que los resultados obtenidos son teóricos. Por esta razón, procesos como *sun glint*, oleaje, ruido, etc. deberían ser considerados en una clasificación real de imágenes.

- El sensor hiperespectral aeroportado AHS puede ser utilizado con éxito en la diferenciación de los tres grupos algales cuando estos se encuentran emergidos. Sin embargo, la diferenciación entre algas pardas y rojas no es posible cuando éstas se encuentran sumergidas. Estos resultados son consecuencia del comportamiento multiespectral en la región del visible del espectro electromagnético y del ruido presente en las imágenes analizadas. La resolución espacial de AHS es útil en la diferenciación de algas verdes, pardas y rojas. Sin embargo, la resolución espectral podría ser una limitación para el cartografiado de hábitats bentónicos poco profundos dependiendo del objetivo del estudio. En nuestro caso la diferenciación entre algas verdes y pardas fue posible hasta 5 m mientras los fondos arenosos pudieron ser diferenciados hasta 8 m debido a sus elevados valores de reflectancia.

- Utilizando el sensor CASI-2 pudieron ser diferenciados entre sí algas verdes, pardas y rojas así como arena cuando estos sustratos se encuentran emergidos. Por otra parte, cuando los sustratos están sumergidos, el modelado bio-óptico mostró que el sensor CASI-2, se podrían diferenciar entre sí los tres grupos de algas (verdes, pardas y rojas) hasta 4 m de profundidad. Además, los grupos de algas podrían ser diferenciados de fondos de arena hasta 12 m. La diferenciación a nivel de especie utilizando las bandas espectrales de CASI-2 muestra algunas dificultades. Por una parte su firma espectral está altamente correlacionada debido a que su composición química es muy similar dentro de un mismo grupo y por otra parte existe una elevada variabilidad intraespecífica. De las especies analizadas las más diferenciables son: *Codium tomentosum*, *Laminaria saccharina* and *Corallina officinalis.* Las diferencias presentes en la región infraroja del espectro podrían dar más información a cerca de la diferenciación a nivel de especie; sin embargo, estas longitudes de onda se pierden cuando las algas se encuentran sumergidas.

- Los clasificadores que mostraron los mejores resultados en las imágenes analizadas fueron Maximum Likelihood y Spectral Angle Mapper (SAM) basados en áreas de entrenamiento establecidas durante el trabajo de campo o datos espectrales respectivamente. La interpretación visual muestra también buenos resultados. Sin embargo, este último método requiere de un elevado conocimiento del área de estudio que permita determinar de forma apropiada cada clase y para una correcta interpretación de la imagen.

- La imposibilidad de diferenciar entre algas pardas y rojas en la zona sublitoral no sería un handicap muy importante en la costa gallega debido a la composición de las especies de algas presentes. Las algas pardas de gran porte son las especies predominantes en esta zona formando densas poblaciones que pueden alcanzar el 100% de cobertura. Las algas rojas se encuentran a menudo como sustrato basal y no pueden ser detectadas por sensores remotos.

- La elección correcta de un sensor no sólo en la costa gallega sino también en otras localizaciones dependerá de cada estudio específico y del objetivo a alcanzar. Sin embargo, en ambientes heterogéneos la elevada resolución espacial es preferible a la elevada resolución espectral.

- Hasta el momento, los estudios realizados en la costa gallega sobre las algas bentónicas se apoyaron en la utilización de métodos convencionales (transectos, cuadrados, etc.) basados en observaciones directas y cubriendo áreas reducidas. Una adecuada gestión a gran escala no sería posible debido a que los datos de cobertura algal se encuentran disponibles sólo para áreas reducidas y existe una falta de continuidad de estos datos en el espacio y el tiempo. En este estudio demostramos que la utilización de teledetección puede ser una alternativa a los métodos convencionales en la creación de mapas temáticos precisos. Sin embargo, se debe de tener en cuenta que los mapas resultantes solo representan una imagen instantánea en el tiempo y la fiabilidad de su representación a cualquier momento posterior dependerá del grado de variabilidad natural presente del área representada en el mapa.

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